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MASTER

HEAVY WATER ORGANIC COOLED REACTOR

FUEL IRRADIATION EXPERIMENT EXP-NRU-305 ALTERNATE I

AEC RESEARCH AND DEVELOPMENT REPORT

ATOMICS INTERNATIONAL—COMBUSTION ENGINEERING

A Joint Venture for Heavy Water Organic Cooled Reactors

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AI-CE-75
METALS, CERAMICS
AND MATERIALS

HEAVY WATER ORGANIC COOLED REACTOR

FUEL IRRADIATION EXPERIMENT EXP-NRU-305 ALTERNATE I

By

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ATOMICS INTERNATIONAL-COMBUSTION ENGINEERING
A Joint Venture for Heavy Water Organic Cooled Reactors

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ABSTRACT

The U-305 A1 experiment was the second in the U-305 series of fueled irradiations in support of the HWOCR program. The irradiation was conducted in the organic cooled U-3 loop in the AECL-owned NRU reactor at Chalk River, Ontario. The fuel string consisted of three SAP-clad UC bundles and two Zircaloy-4-clad UO_2 bundles.

The fuel string operated very satisfactorily for 17 months at design conditions of 20.8 kw/ft peak power rating, 326,000 Btu/hr-ft² peak cladding heat flux, and reached a record burnup on the SAP-UC fuel of 16,700 Mwd/MTU (peak) and a peak burnup of 14,000 Mwd/MTU on the Zr- UO_2 fuel.

Two promising organic coolants, Santowax OM and HB-40, were tested. Both coolants performed well as heat transfer media with coolant outlet temperatures ranging from 653°F (345°C) to 752°F (400°C) and high boiler contents ranging up to 30 wt %.

Surface film formation was studied and found to be dependent on the water concentration in the coolant. Rapid film deposition was initiated when the water concentration was lowered to less than 50 ppm, and it was terminated when the water content was raised to ~300 ppm. No problems with film formation were encountered as long as the water content was maintained at approximately 300 ppm.

This experiment showed that coolant impurity levels can be much higher than levels previously considered acceptable in organic cooled systems. Although the normal indices of coolant purity were allowed to rise to levels heretofore thought unacceptable, the fuel continued to operate satisfactorily without fouling.

Elaborate coolant cleanup systems were not necessary in the U-3 loop. A small side stream flow through an attapulugus clay column and glass spool filter has been sufficient to keep U-3 coolant acceptably clean.

The fuel operated satisfactorily for 4-1/2 months after it defected without organic logging, fuel-coolant interaction or catastrophic failure of the cladding. Radiation levels on the main loop piping remained at 40 to 50 mr/hr even after many temperature and reactor cycles. With non-defected fuel, the radiation

levels on main loop piping at full power were typically 10 mr/hr. The fuel was removed during a routine scheduled shutdown, primarily because the highly burned-up fuel had become a reactivity load and could no longer run at full power.

The long and successful operation of U-305 A1 at high power and high coolant temperature has been the most important single experiment in demonstrating the technical feasibility of the organic-cooled SAP-clad UC system.

I. INTRODUCTION

EXP-NRU-305 Alternate 1 (hereafter designated as the U-305 A1 Experiment) was designed and fabricated as a part of the joint venture between Atomics International and Combustion Engineering (AI-CE) in support of the Heavy Water Organic Cooled Reactor Program (HWOCR). The U-305 A1 experiment was the second of three fuel strings constructed for the purpose of materials evaluation as applied to the HWOCR concept. The main objective of the U-305 test series was to establish long-term performance capabilities in the areas of materials compatibility, fuel stability, fission gas release, cladding effectiveness, film formation rate, thermal hydraulic performance, and coolant chemistry requirements at burnups of 10,000 Mwd/MTU or greater for the UC and UO_2 fuels, clad in SAP and Zircaloy-4.

During the U-305 A1 experiment, coolant chemistry tests were performed to explain some anomalies observed during the U-305 experiment. Emphasis was placed on understanding (1) the effect of water on surface film formation, (2) the effect of coolant impurities on film formation, (3) comparison of Santowax OM with HB-40, and (4) hydraulic performance of the fuel-coolant system.

The ability of the U-305 A1 experiment to meet its objectives was to a large extent dependent on the similarity of its design, operating conditions, and performance with the reference HWOCR demonstration plant design. This requirement was fulfilled, as shown by Table 1, which compares the basic design, and operating parameters of the HWOCR and the U-305 A1 system. Details of these systems can be found in Reference 1, 2 and 3.

The U-305 A1 fuel string assembly consisted of three Sintered Aluminum Product (SAP) clad UC fuel bundles mounted in tandem with two Zircaloy-4 clad UO_2 fuel bundles, as illustrated in Figure 1. A detailed description of the fuel string is given in Appendix A.

The organic cooled U-3 loop in the NRU Reactor at Chalk River, Ontario, Canada, was the irradiation facility used for the U-305 A1 test. The loop was made available to the HWOCR fuel irradiation testing program under a memorandum of agreement between the USAEC and the Atomic Energy of Canada, Ltd. (AECL), who owns and operates the NRU Reactor. This loop is of carbon steel

TABLE 1
COMPARISON OF HWO CR DESIGN AND U-305 A1
OPERATING PARAMETERS*

	HWO CR Design	U-305 A1
Physical Configuration	37-pin hexagonal array	18-pin circular array
Cladding and Fuel	SAP-UC	SAP-UC and Zircaloy- UO_2
Coolant	Santowax OM + 10% HB	Santowax OM + 10 to 30% HB HB-40 with 22-33 wt % HB
Fuel U^{235} Enrichment (%)	1.3	1.5
Pressure Tube In-Core L/D	54.6	33.3
Fuel Area/Pressure Tube Area	0.435	0.438
Fuel Surface Area/Fuel Volume (ft^2/ft^3)	0.706	0.669
Peak Unperturbed Neutron Flux ($\text{n}/\text{cm}^2\text{-sec}$)	2.8×10^{14}	2.4×10^{14}
Peak Initial Specific Power (Mw/MTU)	48.1	46.8
Peak Cladding Heat Flux ($\text{Btu}/\text{ft}^2\text{-hr}$)	298,000	326,000
Peak Fuel Temperature (°F)	2100	2000
Peak Cladding Temperature (°F)	870	850
Bulk Average Power Density (Mw/ft^3 core)	4.11	3.96
Bulk Average Core Coolant Temperature (°F)	662	May 1966 June 1967 to June 67 to Oct 67 617°F 671°F 22 days in 1967 716°F
Coolant Velocity (ft/sec)	30	30
Average Core Coolant Pressure (psi)	217	250

*For U-305 A1, all parameters are for UC elements unless otherwise stated.

Figure 1. U-305 A1 Test Assembly

construction, with the exception of the Zircaloy-4 pressure tube, and has a maximum rating of 4.5 Mw at a test section outlet temperature of 800°F (427°C) and a pressure of 600 psia. The loop consists of three primary subsystems, main loop, degasifier system, and purification system. A detailed description of the loop is given in Appendix B.

Irradiation of the U-305 A1 fuel string began in May 1966 and was terminated 17 months later, in October 1967. In April 1967, in accordance with the termination plan for the HWOCR Program, the responsibility for the U-305 A1 experiment was transferred to the AECL. AECL's objective, to continue operation as a coolant chemistry experiment in support of their organic reactors development program, was similar to that of the HWOCR Program. Therefore, this report covers the entire life of the U-305 A1 experiment.

II. EXPERIMENT OPERATIONAL HISTORY

A. PRE-IRRADIATION EVENTS

The U-305 A1 fuel string was assembled at the Chalk River National Laboratories (CRNL) by Atomics International and Combustion Engineering technicians. The three instrumented SAP-UC fuel bundles and the fuel string hardware were fabricated at AI and shipped to CRNL. The two Zircaloy - UO_2 bundles were fabricated for CE by Canadian Westinghouse at their Port Hope, Ontario facility. Assembly of the fuel string consisted of installing the SAP-UC bundles, and then the Zircaloy - UO_2 bundles, on the hanger rod. The lower end hardware was positioned and a load of 300 pounds force was applied to the fuel bundles by compressing the string with an adjusting nut. The hanger tube was slipped over the thermocouple leads and welded to the upper end hardware and hanger rod. Finally, the instrumentation leads passing through the graphite seal were spliced to the connector.

The U-305 experiment was removed from the U-3 loop on April 18, 1966. Following its removal, a dummy element was inserted and purification of the coolant was accomplished. Prior to insertion of the U-305 A1 experiment, the test section was drained and the pressure tube was gaged.

B. INITIAL OPERATION

The U-305 A1 experiment was inserted in the U-3 loop of the NRU reactor on May 11, 1966. Following insertion, the design coolant flow rate of 16.5 kg/sec was established. The electrical heaters in the loop were used to supply heat to the coolant and thus calibrate the fuel string thermocouples (chromel-alumel) against the loop resistance temperature detectors. Calibrations were made at 200, 250, 300, and 350°C. One thermocouple was inoperative but was later repaired by an electrical discharge technique.

Nuclear operations of the U-305 A1 experiment began on May 12, 1966. For a brief period, the experiment was limited by the reactor power, but after "at power" loading changes, the proper correspondence between reactor power and experimental power was obtained. By May 13, 1966, the experiment was operating at 97% of design power. Table 2 compares the U-305 A1 operational data after one week of operations with the design values. Comparison of the calculated

TABLE 2
COMPARISON OF U-305 A1 DATA WITH DESIGN VALUES

Parameter	Design	Measured
Inlet Coolant Temperature (°F)	572*	571
Coolant ΔT (°F)	82	81
Coolant Velocity (ft/sec)	30	30
Coolant Flow Rate (kg/sec)	16.9	16.5
Experiment Power (Mw)	1.66	1.61
Inlet Pressure (psig)	300	300
Test Section Pressure Drop (psi)	85	88
Maximum Cladding Temperature (°F)	805*	792
Coolant Impurity Water Content (ppm)	100 $\pm$ 50	330
Iron Content (ppm)	2	2
Ash Content (ppm)	5	5
Chlorine Content (ppm)	2	2
High Boiler Content (wt %)	20	15 $\pm$ 5

*Design inlet temperature was 620°F but the experiment operated at 572°F inlet for coolant chemistry tests. The design maximum cladding temperature was correspondingly lowered.

value and measured values at design conditions shows the validity of the thermal, hydraulic, and nuclear analytical models used in the design.

During the first week of operation, no increase in cladding temperature or the corresponding β parameters* was noted under the condition of 300°C inlet temperature, clean coolant, and 300 ppm water content. This result indicated that the early fouling period observed with the previous U-305 experiment was not a general feature of a new element. It furthermore supported the postulate that the fouling observed early in the irradiation of the U-305 experiment was the result of low water content.⁽⁴⁾

*The β parameter is defined in Section III.

C. LONG TERM IRRADIATION

Representative operating history plots for the U-305 Al experiment are shown in Figures 2 through 5, and the following chronology describes those events believed to be important.

Following startup, the experiment was operated with an inlet temperature of 572°F to establish baseline conditions for future tests. In late May, a leakage of coolant from the graphite seal at the top closure was noticed.

On June 25, 1966, the graphite seal catastrophically failed, resulting in a reactor outage. After repacking the seal and adding about 250 gallons of coolant, the experiment was again returned to power.

In early June, difficulties were encountered with the Cr-Al thermocouples. These were the result of open circuits in the alumel leg, which are believed caused by difference in thermal expansion between the thermocouple and the cladding material. This phenomenon had also occurred with the U-305 experiment.⁽⁴⁾ As a result, it was decided to use the chromel-to-stainless steel sheath junction as a thermocouple. This required calibration during each outage.

In mid-June, the measured coolant temperatures at the interface between the SAP-UC bundle (LTA) and the Zr- UO_2 bundle (JRA) began to show an increase in temperature which leveled out about mid-July. This situation, illustrated in Figure 6, implied a change in the power generation ratio between the two lower Zr- UO_2 bundles and the three upper SAP-UC bundles. The total power generation and the indicated flow rate remained constant. The flux monitor data indicated that no change in flux distribution had occurred. It was concluded that either the local flow perturbation had occurred or that the position of the thermocouples in question had physically changed. To resolve any doubt regarding the calibration of the thermocouples, they were calibrated in-situ against resistance temperature detectors (RTD) which had been externally calibrated in a salt bath. No discrepancies were noted. Examination of the experiment in the hot cell may provide a solution to this unexplained change.

Also, about mid-June, the measured pressure drop across the test section showed a substantial increase, which is shown in Figure 5. Although the dp cell used to measure the pressure drop had a history of questionable calibration stability, other instrumentation supported the fact that an increase had occurred.

Figure 2. U-305 A1 Power and Coolant Flow Rate History

Figure 3. U-305 A1 Flux Monitor History

Figure 4. Temperature and β Parameter Histories of TC 21 and TC 22

Figure 5. Temperature and β Parameter Histories of TC 6 and TC 16

Figure 6. U-305 A1 ΔT Split

An extensive analytical investigation revealed no cause for the observed phenomenon. However, this situation led to the rework of the test section hydraulic instrumentation in September.

Beginning on July 8, 1966, the coolant inlet temperature was raised from 572 to 617°F for a period of 4 weeks. As expected, the cladding temperatures increased correspondingly. The water content was held at a nominal value of 300 ppm. While operating under these conditions, no rising trends in cladding temperatures or β parameters were observed, thus indicating that it was possible to operate the element at this temperature, in clean coolant containing 300 ppm water, with little or no fouling.

On August 3, 1966, the control of coolant temperature was changed from the test section inlet temperature instrumentation to the test section outlet instrumentation. This was done to provide greater flow stability by keeping a constant coolant temperature at the flow orifice.

On August 8, 1966, with an outlet temperature of 653°F, the water content was lowered to less than 50 ppm. On August 21, 1966, the water content was again restored to 300 ppm. During the intervening period, positive indications of fouling were not obtained. The cladding temperatures increased from 18 to

Figure 7. U-305 A1 Flow ΔP Test

Figure 8. U-3 Dummy Element Flow ΔP Test

27°F at those instrumented positions where observed cladding temperatures were above 757°F. The low water test was concluded because other reactor experiments required power cycling which would not allow interpretation of the data. A decrease in the Mg^{27} activity was also observed. In early June, analysis of the coolant revealed the presence of Mg^{27} . This nuclide results from the $Al^{27}(n,p)Mg^{27}$ reaction at the surface of bare SAP cladding and its presence in the coolant suggests that no significant fouling film was present prior to the beginning of the low water run. The decrease in Mg^{27} activity also suggested that fouling had occurred during the low water tests since any film formation would retard its entrance into the coolant.

During the September 19, 1966 shutdown, the following work on the U-3 loop was accomplished:

- 1) The loop cooler was repaired.
- 2) The main flow transmitters were relocated.
- 3) Two new differential pressure transmitters were installed.
- 4) Two pressure transmitters were installed.
- 5) A new thermocouple patch panel was installed.
- 6) The graphite seal on the U-305 Al top closure was repacked.

As mentioned previously, the pressure drop across the test section had been erratic. Although the pressure drop at the initiation of the experiment was felt to be reasonable, there was considerable doubt regarding the veracity of the measurements subsequent to this time. For similar reasons, interpretation of the hydraulic performance of the U-305 experiment had been difficult. Following the rework, hydraulic tests were performed. The results, shown in Figure 7, indicate that, at this point in time, performance of the instrumentation was satisfactory. Repacking of the graphite seal was not completely successful. The leak at the graphite seal became progressively worse and on November 15, 1966 the U-305 Al experiment was removed from the U-3 loop and placed in the storage cell. A dummy element was inserted in the U-3 loop and flow-pressure drop tests were performed to verify instrument performance (Figure 8). The experiment was reinstalled in the loop on November 28, 1966; pressure measurements with both static and flowing coolant are shown in Figure 7.

The primary reason for removing the U-305 A1 experiment from the loop to the storage block was to substitute a brazed seal for the leaking graphite seal. Similar seals had already been installed on the U-305 A2 experiment and the WR1-951 experiment. Replacement of the seal also provided an opportunity to repair some thermocouple leads which had been damaged during repacking of the graphite seal. Moreover, visual inspection of the zirconium specimens attached by two studs each to the hanger rod showed that approximately one-half of the 42 specimens were loose, that 4 were held by only one stud, and that one was completely detached and lying in pieces on the lower screen. Because of potential problems, all of the specimens were removed before operation was resumed.

Inspection of the pressure tube was also performed during this period. The inspection consisted of a borescope visual examination and measurements. The pressure tube was inspected prior to the insertion of the U-305 A1, and at that time showed no discernable evidence of wear or damage. However, during this inspection, evidence of wear was observed at axial elevations corresponding to the top spacer ring of the uppermost fuel bundle and the lower hanger tube guide ring located ~ 18 in. above the top fuel bundle. The wear marks extended over an arc of $\sim 100^\circ$ at opposite sides of the pressure tube. The bottom wear mark was estimated to be ~ 2 to 5 mils in depth, while the upper mark was estimated to be ~ 10 to 15 mils in depth. Based on this observation it was decided to conduct the inspection of the pressure tube at intervals throughout the period of irradiation.

The pressure tube was gaged during scheduled reactor shutdowns in January, June, and October of 1967; no new fret marks, or increase in the depth of the existing marks were observed on any of these occasions.

On December 22, 1966, both clay columns in the U-3 loop system were put on line with new clay, in preparation for another low water test. On December 27, 1966, the water addition was valved out and water content lowered to <50 ppm. The conditions during this test were similar to those on August 8, when rapid film formation was observed, with the exception that two fresh clay columns had been used to clean up the coolant just prior to the test. Except for the temperatures indicated by T/C 8 and T/C 24, the expected temperature increase did not occur, and on January 6, 1967 the No. 1 clay column was taken out of service in an attempt to increase the impurity level. However, no significant effect was

observed. The temperature indicated by T/C 24 rose to its maximum allowable limit, 850°F, and at this point the low water test was terminated by a rapid injection of water. Temperature increases ceased.

On May 1, 1967, responsibility for the experiment was shifted to AECL because of the USAEC HWOOCR termination. The U.S. site representatives remained at the site to continue the irradiation program under the direction of AECL. The test program developed in this new regime was directed toward the support of the WNRE organic reactor concept and was as follows:

- 1) The irradiation of Santowax OM would continue until sufficient physical properties information was obtained. Then the coolant would be changed to HB-40.
- 2) The HB content would be allowed to increase to 30%.
- 3) The clay column endurance test would be continued.
- 4) The outlet temperature would be raised in steps to 750°F.
- 5) The U-305 Al experiment would be operated until it defected.

In June a burst of fission product gases occurred during some hydraulic transients in the U-3 loop. Other power, temperature, and hydraulic transients over the next several months caused similar bursts, none of which was so large as to double the gamma activity of the coolant, but there was definitely a cladding defect which gradually worsened over the period of 4-1/2 months.

On June 27, 1967 the loop outlet temperature was raised to 707°F. No significant effect on the β parameters was noted. On July 17, the water content was lowered from 300 to 25 ppm to see if fouling would occur. For the first time in six months a significant increase in temperatures and β parameters on all operable cladding thermocouples was observed. Following restoration of the water content to 300 ppm on July 26, the temperatures and β parameters leveled off. This test was significant in that it showed that low water content induced fouling and that the presence of water can inhibit fouling even in coolant which is considered dirty. The MST^* value had reached $7820 \times 10^{-5} \text{ A/mg}^*$ and

*The term "MST" is described in Reference 4; the term "A/mg" is described in Reference 7.

TABLE 3
 REPRESENTATIVE U-3 LOOP CONDITIONS BEFORE AND AFTER
 RAISING OUTLET COOLANT TEMPERATURES TO 400°C
 (752°F)

	July 31 0850		July 31 1521	
T out (°C)	375		401	
T in (°C)	335		362	
ΔT (°C)	40.2		39.6	
Flow (kg/sec)	16.26		16.22	
Q (%)	96.6		98.0	
ΔP (psi)	110.4		112.4	
Outlet pressure (psi)	214		206	
Fuel	Temperature (°C)	β	Temperature (°C)	β
T/C 16	431	1.65	452	1.55
T/C 9	428	1.76	451	1.70
T/C 11	426	1.53	449	1.47
T/C 8	425	1.68	448	1.61
T/C 6	421	1.57	444	1.53

the electrical conductivity had reached 1960 picohms/cm, as shown in Figure 2. A flow reduction test was then performed.

On July 31 the outlet coolant temperature was raised to 400°C (752°F) for 11 days with no increase in β parameters. Table 3 shows representative data before and after raising coolant temperature.

During the August 18, 1967 reactor outage, tests were conducted with only one pump. The purpose of these tests was to evaluate the possibility of operating a fuel string in a nucleate boiling mode where the pressure would be lowered to about 100 psig (normal 215 psig). The normal two-pump operation mode creates a large pressure drop across the flow control valve downstream of the test section.

The results of this test are as follows:

- 1) One pump operation produced a full flow of 15.3 kg/sec, or 280 gpm at 662°F and an HB content of 29%. This compared favorably with the nominal two-pump flow of 16.2 kg/sec.
- 2) Flow stability was excellent.
- 3) Pump suction pressures were lowered to 47 psig before vapor release occurred.

Between August 19 and August 25, the OM coolant was drained from the loop and the loop was flushed and then filled with HB-40 which had been removed from the B loop of the WR-1 reactor at WNRE. Circulation was resumed with a coolant temperature of 300°C (572°F). The flow control was set to give the same volume flow rate as when OM had been the coolant (306 gpm). This resulted in a mass flow rate of 15.6 kg/sec at 350°C (662°F) average bulk coolant temperature with a density of 0.81 gm/cm³ at a nominal HB concentration of 20 wt %.

During pump startup an activity release to the coolant was observed. A coolant sample revealed the presence of fission gases or daughter products, namely Kr⁸⁸, Kr^{85m}, Rb⁸⁸, and Xe¹³⁵. This was the largest release observed thus far on the U-305 A1, but the level was a factor of 7 less than the initial release of the U-305 experiment. The activity disappeared within 18 hours.

The reactor was taken to power on August 28, 1967 and the coolant outlet was raised to 707°F on August 30. A comparison of the loop and fuel string performance with the two different coolants is shown in Table 4, which includes data for OM coolant with two different HB contents. The conclusions that can be drawn from the table are:

- 1) At 24% HB at 30 ft/sec velocity, the difference in pressure drop across the test section is less than 1% for the two coolants.
- 2) The change in pressure drop between OM and HB-40, both with 25% HB, is much less than the pressure drop resulting from a change of 24 to 28% in OM.
- 3) Pumping power for the same volume flow rate is the same for the two coolants.

TABLE 4
COMPARISON OF THE LOOP AND FUEL STRING PERFORMANCE
WITH THE OM AND HB-40 COOLANT

	7-19-67		8-12-67		9-3-67	
Coolant	OM		OM		HB-40	
HB (%)	24.1		28.0		24.0	
Inlet Temperature (°C)	336.5		337.0		337.7	
Outlet Temperature (°C)	375.9		376.5		375.9	
ΔT (°C)	39.4		39.4		38.2	
Q (%)	94.4		94.7		94.6	
Average Measured Flux (nvt x 10 ⁻¹⁴)	1.07		1.095		1.118	
Mass Flow Rate (kg/sec)	16.18		16.21		15.66	
Density (g/cm ³)	0.855		0.861		0.821	
Viscosity (g/cm-sec)	0.004		0.0046		0.0037	
Volume Flow Rate (gpm)	299.9		298.4		302.3	
Average Velocity (ft/sec)	30.0		29.9		30.2	
Inlet Pressure (psia)	335.7		339.4		334.2	
Outlet Pressure (psia)	213.7		212.3		214.2	
ΔP 81 (psi)	108.6		113.5		107.5	
ΔP 82 (psi)	120.4		125.5		119.9	
Pump Current No. 1 (amp)	43.5		42.0		42.0	
Pump Current No. 2 (amp)	44.3		44.5		45.0	
Thermocouple Number	Temperature (°C)	β Parameter	Temperature (°C)	β Parameter	Temperature (°C)	β Parameter
T/C 6	417	1.48	418	1.49	413	1.41
T/C 8	422	1.60	406	1.19	401	1.10
T/C 9	424	1.67	422	1.59	-	-
T/C 11	423	1.46	422	1.43	-	-
T/C 14	402	0.94	403	0.95	402	6.96
T/C 16	432	1.70	-	-	-	-
T/C 18	403	0.93	408	1.04	407	1.03
T/C 19	415	1.22	415	1.20	407	1.03
T/C 22	414	1.19	413	1.16	412	1.17
T/C 23	402	0.89	403	0.91	401	0.89

4) Fuel surface temperatures are the same, or slightly lower, with HB-40 at 30 ft/sec than with OM.

5) The thermal power (Q) with the two coolants is virtually the same.

By September 5, activity release in the form of spikes was noted with every reactor trip, shutdown, and power change. Most of the activity transients decayed to about 70% of the maximum in 5 to 6 hours. The normal activity around the loop was less than 10 mr/hr and rose to only 50 mr/hr during a spike.

Another concern was the high burnup obtained by the fuel. Since the experiment was being operated at constant power, burnup had to be compensated for by steadily increasing the local neutron flux. Continuation of this philosophy would soon compromise reactivity limits established for the NRU. In addition, cobalt production in the control rods near the U-3 loop was being reduced. It was therefore decided to remove the U-305 A1 from the reactor during the October 16 shutdown unless it had failed earlier. "Failure" in this case would be defined as an activity level, as indicated by the loop monitor, of 50,000 cpm on a rising trend with steady full power. Operation continued until October 15, 1967 when the NRU was shut down as scheduled. After the 32 hours cooling, the U-305 A1 was removed from the reactor and placed in the storage block in clean HB-40. Visual examination of the string was scheduled for March 1968. The U-305 A2 was inserted in the U-3 loop on October 20 with one of its primary objectives being to study nucleate boiling. The U-305 A1 fuel string had operated for 17 months and had accumulated peak burnup levels of 16,700 Mwd/MTU and 14,000 Mwd/MTU on the UC and UO_2 fuels respectively.

D. POST IRRADIATION

The U-305 A1 experiment remained 4-1/2 months in HB-40 in the storage block. Just prior to removing the string, the element was rinsed in xylene by pumping the HB-40 from the bottom of the storage hole (via a 3/8-in. tube which had been installed prior to putting the experiment in the hole) and adding xylene at the top. The element was allowed to stand in xylene approximately 1 hr before being lifted into the transfer flask and transported in air to the CRNL Universal Cells. This was the first time the experiment had been exposed to air since it was installed in the loop in May 1966.

The fuel string was visually examined in the Universal Cells and dismantled and 2 bundles (LRA, LTA) were sent to WNRE for detailed examination. The results of the post-irradiation examination will be published by AECL.

III. RESULTS

The objective of the U-305 A1 experiment was to provide information on fuel coolant and loop performance. From an engineering viewpoint these objectives were met or exceeded. In addition to the major objectives, other information was obtained which should prove useful to other irradiation experiments, and are therefore discussed.

A. FUEL

The U-305 A1 experiment operated for 17 months and achieved peak burnups of 16,700 Mwd/MTU and 14,000 Mwd/MTU on the UC and UO_2 fuel respectively. During the last five months of operation, the experiment was operated with one or more defected fuel rods as evidenced by increasing radiation levels, increasing frequency of radiation spikes with changes in loop condition, and the presence of fission gases in the coolant. No radioiodine was detected, and only trace amounts of non-gaseous fission products were observed. Regardless of whether the SAP-clad UC or Zr-clad UO_2 defected, it is significant that the experiment was operated at or near full power for this long a period after the first indicated defect, without creating any operational problems. The normal activity at the main loop piping was 10 mr/hr which increased to a maximum of only 50 mr/hr by the time the fuel was removed.

B. COOLANT

The design coolant for HWO CR was Santowax OM with 10% HB. This composition was chosen because it optimized coolant decomposition and physical properties. For this reason the coolant HB content was maintained between 10 to 20% until the program was transferred to AECL. AECL's design coolant was HB-40 with 30 to 40% HB. Therefore, AECL desired to measure decomposition rates and physical properties of both HB-40 and Santowax OM at similar conditions. For this purpose the HB content of the Santowax was allowed to rise. The physical property data and decomposition rate data are compared in Tables 5 and 6. The decomposition to low boiling components is negligible with Santowax OM. However, with the HB-40, the formation rate of low boilers was 4.2 and 16.5 lb/Mwd at 375 and 400°C respectively. Gas formation rate ranged

TABLE 5
COMPARISON OF PHYSICAL PROPERTIES OF
SANTOWAX OM AND HB-40

Date	HB (wt %)	Density (g/cc)				Viscosity (cp)			
Santowax OM									
Temperature (°C)		250	300	350	400	250	300	350	400
Dec. 20, 1966	12.0	0.915	0.878	0.838	0.795	0.659	0.457	0.327	0.246
May 23, 1967	16.6	0.922	0.884	0.849	0.811	0.738	0.495	0.365	0.276
June 28, 1967	19.7	0.927	0.890	0.850	0.816	0.806	0.543	0.400	0.294
July 31, 1967	27.2	0.937	0.900	0.876	0.825	1.078	0.630	0.473	0.347
HB-40									
Aug. 26, 1967	22.7	0.900	0.864	0.828	0.790	0.792	0.544	0.406	0.316
Sept. 14, 1967	24.9	0.901	0.868	0.835	0.799	0.829	0.582	0.418	0.312
Oct. 4, 1967	28.9	0.906	0.873	0.841	0.807	0.843	0.576	0.437	0.331
Oct. 17, 1967	32.0	0.924	0.891	0.858	0.822	1.026	0.713	0.523	0.403

TABLE 6
HB FORMATION RATES OF SANTOWAX OM
AND HB 40

	HB (wt %)	Outlet Temper- ature (°C)	Formation Rate (lb/Mwd)
Santowax OM	~ 13.0	345	7.5
	~ 18.5	345	6.5
	~ 25	375	8.2
	~ 27	400	~ 29*
HB-40	~ 26	375	12
	~ 33	400	29

*This value is based on only two experimental points

from 0.5 ft³/hr for Santowax OM to 6 ft³/hr for HB-40 at 400°C. A comparison of the loop and fuel string performance with the two coolants was presented in Table 4. These data show that HB-40 is a slightly better heat transfer fluid than Santowax OM.

The auto ignition temperature (AIT) of new Santowax OM coolant is 500°C, while the AIT of new HB-40 is ~390°C. However, it was found that, when the loop was operated at 375°C, the AIT increased to ~425°C and, when the outlet temperature was increased to 400°C, the AIT increased to ~440°C. Each addition of new HB-40 dropped the AIT ~20° which recovered to 440°C within three days.

It is significant that there were no fires associated with the U-3 loop during the entire duration of the U-305 series of experiments, while either coolant was in use.

Fouling on the heat transfer surface has long been a source of concern for the organic-cooled reactor concept. The U-305-A1 experiment has shown that fouling can be controlled and that the intentional rapid fouling induced three times during this test did not limit the fuel life nor power. Water content of the coolant has been very important in the fouling mechanism; rapid fouling occurs each time the coolant water content is less than 50 ppm and fouling is inhibited when the water is raised to ~300 ppm.

The mechanism of fouling is discussed in Reference 5. From this reference it can be postulated that a catalytic reaction causes fouling and that water poisons the catalyst. If such is the case, the water-to-catalyst ratio would have to be high enough to poison all the catalyst. Such a concept indicates that higher water contents are necessary in dirtier coolants. Also clean coolants may not foul at all, even at low water contents.

To investigate this water effect, which was observed twice during the U-305 experiment,⁽⁴⁾ the water content was intentionally lowered three times during the U-305-A1 experiment. Fouling was observed each time by increases in the β parameters. These data are shown in Table 7. It is significant to note that only those thermocouples reading 750°F or hotter rose during the first test. Only T/C 8 and 24 showed a remarkable increase during the second test, and all thermocouples showed a rise on the third test.

TABLE 7
TEMPERATURE INCREASES DURING LOW WATER FOULING TESTS

Thermocouple Number	Temperature (°C)	β	Thermocouple Number	Temperature (°C)	β
August 8, 1966			August 21, 1966		
6	388	1.45	6	397	1.60
8	398	1.69	8	419	2.09
9	399	1.71	9	424	2.21
11	400	1.56	11	403	1.57
16	410	1.82	16	434	2.26
24	396	1.28	24	403	1.39
December 22, 1966			January 9, 1967		
6	408	1.98	6	415	2.06
8	403	1.85	8	415	2.06
9	399	1.76	9	399	1.70
11	400	1.61	11	410	1.80
16	433	2.41	16	444	2.58
24	401	1.46	24	452	2.70
July 20, 1967			July 26, 1967		
8	423	1.60	8	432	1.78
9	426	1.67	9	420	1.74
11	423	1.47	11	430	1.56
16	435	1.72	16	438	1.75

Flow reduction tests were performed to quantify the thermal resistances of the film at the cladding surface. The loop power and loop flow were simultaneously reduced, in steps from 100 to 50%, while holding temperature constant. The test was based upon the following relationships:

$$P_{(z)} = (T_{j(z)} - T_{c(z)})UA$$

$$P = WC_p \Delta T$$

Expressed as a ratio and transposed, these become:

$$T_j(z) - T_c(z) = \frac{W C_p \Delta T}{UA} \frac{P(z)}{P}$$

where

$T_j(z)$ is the cladding temperature at point (z).

$T_c(z)$ is the bulk coolant temperature at point (z).

$P(z)$ is the local power at point (z).

P is the power of the fuel string.

W is the mass flow rate.

C_p is the specific heat.

ΔT is temperature rise of bulk coolant.

U is overall heat transfer coefficient.

Rearranging, an expression is obtained which is defined as the β parameter:

$$\beta \approx \frac{T_j(z) - T_c(z)}{\Delta T} = \frac{W C_p}{UA} \frac{P(z)}{P}$$

The flow reduction test permits observation of the change in U with changes in W , since β can be easily measured and the other terms remain constant.

The film resistance, r , can be separated from the heat transfer coefficient, h , by the following:

$$R = \frac{1}{U} = \frac{1}{h} + r$$

For β the expression becomes:

$$\frac{W c_p P(z) h}{A P (1 + rh)}$$

Taking the ratio of any measured β to the initial β_o and cancelling like terms,

$$\frac{\beta}{\beta_o} = \frac{(W)}{(W_o)} \frac{(h)}{(h_o)} \frac{(1 + rh_o)}{(1 + rh)}$$

Using the relationship that $h = h_o \left(\frac{W}{W_o} \right)^y$,

$$\frac{\beta}{\beta_o} = \frac{W}{W_o} \frac{\left(\frac{W_o}{W} \right) + r h_o}{1 + r h_o}$$

when h_o is the initial heat transfer coefficient and W_o is the initial flow rate. Thus with any two flows, two corresponding β parameters are obtained and values for terms y and h_o must be ascribed to find r . Values used for the U-305-Al experiment were, $y = 0.9$ and $h_o = 2200$ Btu.

The results of the flow reduction tests are shown in Table 8. The data show a reduction in film resistance between January and June 1967. The reduction is believed to be the result of film flaking from the surface. Films removed from silver membrane filters and the tops of clay columns not only confirm this belief but gave interim film thicknesses. Films removed from filters

TABLE 8
RESULTS OF THE FLOW REDUCTION TESTS
(Thermal Resistance of Fouling Film, r ($^{\circ}\text{F-ft}^2\text{-hr/Btu} \times 10^4$))

Thermocouple Number	January 11, 1967 End of Low H_2O Test	June 2, 1967	July 28, 1967 End of Low H_2O Test
6	2.96	0.31	0.84
7	1.32	out	out
8	1.45	0.79	0.83
9	1.35	1.05	1.95
10	0.95	0.35	-
11	1.46	-	1.29
14	0.19	-	-0.41
16	2.65	2.31	2.47
17	3.64	2.29	-
18	-	-0.24	0.00
19	-0.23	-0.11	0.37
21	1.15	0.20	-
22	0.20	-0.08	0.11
24	16.3	2.02	2.19

in May 1966 (the silver membrane was not used until May 1966) showed the film to be 10 to 20 microns thick. The photomicrographs of a film flake, Figure 9, show the same striations as a similarly magnified photo of typical SAP cladding, which leaves little doubt about the origin of the flake. (In View a, note right angle between the two surfaces and beveled edge at corner.) With removal of the clay column which had been in service for 32 weeks, thousands of film flakes were observed on the surface. After magnetically removing a representative number of flakes from the clay, the flake thicknesses were determined to be 30 to 40 microns. These thicker flakes appeared to be consistent with higher β parameters observed during December 1966 and January 1967. Samples taken from filters between June and September 1967 showed films to range between 1 and 18 microns. It is important to realize that the presence of these films did not limit the fuel life or power.

Several tests were conducted with the U-3 clay columns during the U-305 A1 experiment. It had been demonstrated early in the U-305 program that clay columns could be used to clean-up relatively dirty coolant, i.e., the coolant MST values, electrical conductivity, radioactivity, and chlorine content could be reduced orders of magnitude by frequent changes in clay columns. In fact, the arbitrarily established purity level of $\text{MST} < 15 \times 10^{-5} \text{ A/mg}$ required clay column changes about twice per month for the first one and one-half years of the U-3 program. Such frequency was certainly not practical for an organic cooled reactor and the importance of clay column operation optimization was clear. While this goal has not been accomplished, a few guide lines were established to help future experimenters. Even though it is not known how the efficiency for removal of fouling species varies with temperature, time, and flow rate, some tests were conducted as outlined below.

The clay column temperature was varied over a range of 207°F (115°C) in December 1966. These limited studies gave the following results:

- 1) Operation of the clay column at an inlet temperature of 607°F (315°C) resulted in a rapid increase in MST values.
- 2) Reduction of the temperature to 563°F (295°C) decreased the MST values by about 30%.
- 3) Further reduction to 509°F (265°C) did not significantly reduce the MST values. However, no increase in the MST occurred at this temperature.

a. Film Flake

b. Surface of Film Exposed to Cladding. (Same flake as in (a), higher magnification)

c. Fuel Cladding Surface. (Same magnification as (b))

Figure 9. Comparison of Cladding and Film Flake Striations of Silver Membrane Filter Removed From U-3 Loop, May 1967
(Photographs Supplied by AECL)

- 4) Reduction to 392°F (200°C) caused a slight increase in MST.
- 5) Restoration of the temperature to its normal operation temperature 563°F (295°C) was accompanied by an increase in MST by 30%.

The results indicated that operation of the clay columns with an inlet of ~509°F (265°C) was desirable.

A clay column endurance test was started on December 22, 1966 to determine how long the loop could operate on one column before fuel surface to film formation became a problem. With no indication of fouling after 7-months of operation frequent clay changes appeared unnecessary. At that time, the main interest was to try to compare Santowax OM with HB-40 at nearly identical conditions by reducing the impurity levels of the OM by clay column changes. Besides, WR-1, with its much higher ratio of coolant inventory to clay column size, could enable study of the question of minimum purification more efficiently than could the U-3 loop.

On August 2, 1967, therefore, the clay column was valved out. It had been in service for 32 weeks and during this period the loop had produced 277 Mwd of energy, which corresponds to about 3.1 Mwd/kg of clay. The column had operated at 260 to 305°C (580°F) and a flow rate of 373 to 620 gm/sec. During most of the period it operated at higher flow rate and processed approximately 100,000 gm coolant/gm clay. Several clay column changes were then made over the next two weeks in order to bring the coolant impurity indices down to levels close to those for the HB-40 coolant to be soon added. Table 9 shows the effect of the clay column changes on the U-3 loop impurity indices.

The clay column was filled with 200 lb of clay, and at 620 gm/sec at 295°C, the coolant velocity through the clay was $0.57 \text{ cm}^3/\text{sec per cm}^2$ of column surface ($1.12 \text{ ft}^3/\text{min per ft}^2$ of column surface). At this velocity the pressure drop was 4.5 psi across the clay column. The clay columns were necessarily backed up by glass-fiber-wound spool filters. Less than 2 psi pressure drop was measured across the filters. At no time was there observed any change in pressure drop across either the columns or the filters which could not be attributed to flow rate or temperature. It was not necessary to change the filters throughout the life of the U-305 Al experiment. They were changed at the end to remove them as a radioactive source, since they had picked up fission products caused by the defect.

TABLE 9
EFFECT OF CLAY COLUMN CHANGES ON U-3 IMPURITY INDICES

Date and Time of Column Change (1967)	MST (A/mg x 10 ⁻⁵)	Elect. Cond. (picomhos/cm)	H ₂ O	Radiation (cpm)
Before 1st Change August 2	11,220	2280	204	4300
After 1st Change August 4	5,778	775	213	4450
Second Change August 4	2,382	375	507	5000
No Column August 8	4,082	717	195	4300
Third Change August 9	2,264	273	380	4650
Fourth Change August 9	700	113	1096	6200
Fifth Change August 10	380	75	410	5300
Sixth Change August 11	280	61	893	4400
Seventh Change August 14	163	44	1000	4100
Eighth Change August 15	97	39	934	4100

In addition to the by-pass filtration there were strainers (1/32-in. holes) at the inlet of each main pump. These strainers were inspected several times during the experiment. Only once was there any foreign matter on the screens. This matter was attapulugus clay. Each time a freshly filled clay column is valved into the system, clay gets past the 100 mesh screen at the bottom of the column and is normally picked up by the glass fiber filters. During this single incident the filters were inadvertently by-passed. Clay got into the main loop and some of the clay was removed by the pump inlet strainers. It must also be assumed that some clay which passed through the strainers was removed by the clay columns. No adverse affects were apparent from this incident.

By-pass filtration through attapulugus clay has proved to be sufficient to control the coolant impurity levels. There was a time when it was believed that full-flow filtration was necessary to keep organic cooled systems acceptably clean. The U-3 loop experience is strong evidence to the contrary.

C. INSTRUMENTATION

1. Flux Monitors

There were five Hilborn-type flux monitors attached to the U-3 loop pressure tube. These were installed in July 1965, prior to the irradiation of the U-305 experiment. Four of the five were operating satisfactorily at the end of the U-305 A1 experiment. The other failed early during operation when its internal resistance began to gradually decrease. The flux monitors were extremely useful in that they provided backup information to assist in the resolution of operating anomalies. They also provided trend information in the form of the ratio of the fuel string power generation to the flux as a function of time. The utilization of such detectors is highly recommended.

2. Thermocouples

Considerable difficulty was encountered with the small gage Chromel-Alumel cladding thermocouples. The requirement to imbed these thermocouples in the 0.035-in. wide cladding fins dictated their small size. The sheath OD was 0.020 in. and the wires were 0.003-in. in diameter. Failures were predominantly caused by open circuits in the alumel leg, due to differential expansion between the stainless steel sheath and the grounded T/C wire. As a result, the junction of the chromel leg to stainless steel sheath was used as a thermocouple when required. A parted alumel wire could often be repaired by an electrical discharge welding technique. Frequent in-situ calibration against resistance temperature detectors during reactor shutdowns was required. Similar problems had also occurred with the U-305 experiment and, since the bundles were all fabricated at the same time, the same type of thermocouples had been used. At the termination of the experiment only four of the original 19 surface thermocouples were still in service. Considering the size of the thermocouple, the reasons for its choice, and the length of irradiation, even this performance is remarkable.

Experiments performed since the selection of thermocouples for the U-305 series have demonstrated improved thermocouple reliability. The use of 100% x-ray inspection of the junctions of high density insulation⁽⁶⁾ has been a primary improvement.

3. Loop Instrumentation

Problems associated with the flow and test section pressure drop instrumentation were remedied about a third of the way through the irradiation by relocating transmitters to cooler positions, rearranging the impulse lines to eliminate horizontal runs and gas traps, installing new equipment, and orienting ΔP transmitters to permit self-venting. Since the measurement of flow in a loop experiment such as the U-305 A1 is a critical item, it is recommended that this instrumentation and its installation be given extra special consideration in the future. Frequent measurements of the flow- ΔP characteristics will not only provide information regarding the string but, of equal importance, will reveal instrumentation problems.

4. Data Collection

The U-3 loop and the U-305 A1 experiment data were recorded on REDACE* and strip charts. The capability of REDACE to collect, reduce, store and printout in engineering units the many data points in a short time span proved to be a great asset. The REDACE system took data every 1/2-hr or on demand, and the site personnel could therefore plot the data from one or more sets, being careful to choose a time when reactor conditions were at equilibrium. Later modifications provided the capability to collect and store 16 sets of data and to display the resulting averages. This averaging technique reduced much of the scatter and provided more meaningful data trend information.

A punched card and a magnetic tape capability were part of the CRNL system. The cards or tapes were shipped to AI for data reduction. This aspect proved to be costly and time-consuming, primarily because of the many changes being made to the data collection system. As a result, programming changes were a constant occurrence. The data reduction output commonly lagged the original readout by days or weeks, which was unacceptable to a program which demanded a current daily status. The data reduction process was therefore supplemented by 100% transmittal of current daily REDACE data.

*REDACE is an acronym for REactors DATA CEntre. It is described in Appendix B.

IV. CONCLUSIONS

A. FUEL DESIGN

The fuel string operated at design conditions of cladding temperature, flow, and specific power, thus verifying the suitability of the analytical techniques for design of SAP-clad UC rod bundles in organic cooled systems.

The actual operating conditions of this first generation fuel experiment were essentially the same as those specified for the reference HWOCR demonstration plant design.

B. BURNUP

The 16,700 Mwd/MTU peak burnup achieved by the SAP-UC fuel was somewhat higher than the 10,000 Mwd/MTU nominal design target and also about 50% higher than the peak burnup achieved in any prior SAP-UC irradiation. Peak burnup on the Zr-UO₂ portion of the string was 14,000 Mwd/MTU, based on integrated heat output of the fuel during its 17-month irradiation.

C. DEFECT

Although the fuel string had developed a defect (or defects) after one year of operation, it continued to operate satisfactorily at or near full power for 4 to 5 months without creating any operational problems or resulting in a catastrophic rupture. Only fission gases were released to the coolant during the many bursts of activity, and their net effect was to raise the radiation levels on the main lines from <10 mr/hr to ~50 mr/hr at full power. Because the post-irradiation examination has not been performed, the location and nature of the fission release defect(s) are not known.

D. TWO COOLANTS

Two promising organic coolants, Santowax OM and HB-40, were tested at the same conditions, on the same loop with the same fuel string, one right after the other. Both coolants performed well as heat transfer media with coolant outlet temperatures ranging from 653°F (345°C) to 752°F (400°C) and high boiler contents ranging up to 30 wt %. Due to higher specific heat and generally lower viscosity, HB-40 had a slight advantage in heat transfer coefficient, but Santowax OM showed lower HB formation rates at 375°C outlet.

Because the loop was trace-heated, there was never a freezing problem with either coolant. The Santowax OM was always a liquid at room temperature even though HB content reached a minimum of 10 wt %.

There were no fires with either coolant during the U-305 series experiments in the U-3 loop.

E. FOULING

The dependence of film formation on water concentration in the coolant, which was observed during the U-305 experiment, was verified during the present U-305 A1 experiment. Rapid film deposition was initiated when the water concentration was lowered to less than 50 ppm and was halted when the water concentration was raised to ~ 300 ppm. No problems with film formation have been encountered in more than two years of U-3 loop experiments as long as the water content is maintained in the range of a few hundred ppm. The acceptable upper and lower limits of water content have not been established. The range of 100 to 2000 ppm has been experienced in the U-3 loop with no observable ill effects.

F. COOLANT IMPURITIES

Reasonable care was exercised to exclude oxygen and other impurities from the coolant system, but this experiment showed that coolant impurities can be much higher than levels previously considered acceptable in organic cooled systems. Although electrical conductivity had been allowed to rise to as high as 2280 picomhos/cm and the MST to as high as $11,200 \times 10^{-5}$ A/mg, the fuel continued to operate satisfactorily without fouling. In these impurity ranges, at least, the presence of approximately 300 ppm of water is effective in inhibiting film formation.

Elaborate coolant cleanup systems were not necessary in the U-3 loop. A small side stream flow through an attapulugus clay column backed up by a glass spool filter has been sufficient to keep the U-3 coolant acceptably clean, with only infrequent change of adsorbent material.

Chlorine impurity was not considered a problem. It was accidentally admitted to the system only once and it was immediately detected by its pronounced gamma activity and was easily and quickly removed by the clay column.

APPENDIX

A. DESCRIPTION OF THE U-305 A1 FUEL STRING

1. U-305 A1 Assembly

The U-305 A1 fuel string assembly consisted of three SAP clad UC fuel bundles mounted on tandem with two Zircaloy-4 clad UO_2 fuel bundles, as illustrated in Figure 1. The fuel bundles were mounted on a 3/8-in. stainless steel hanger rod passing through the center of each bundle. The end-plates of adjacent bundles were keyed together and the top end-plate of the uppermost bundle was keyed to the upper retainer assembly to prevent bundle rotation. Where it passed through the fuel bundles, the hanger rod was shrouded by a dummy cladding tube to preserve hydraulic characteristics and to house instrumentation leads running from the test section. An Inconel X spring (Figure 10) was positioned at the bottom of the fuel string assembly to maintain a compressive load and assure nesting of the bundles and to accommodate differential thermal expansion between the fuel bundles and the hanger rod.

The test section was vertically supported in the U-3 loop pressure tube by a hanger tube welded to the upper retainer assembly. The breech block assembly, which was welded to the hanger tube, was seated on the pressure tube extension. The instrumentation leads from the fuel string passed through the breechblock and were sealed with a graphite compression gland. The instrumentation leads were terminated in a connector assembly above the breechblock, and a cable with mating connector connects the instrumentation with the appropriate loop and data retrieval systems. This assembly is shown in Figure 11.

2. Fuel Bundles

a. SAP-UC-Fuel Bundles

The nuclear fuel was arc-cast hyperstoichiometric UC enriched to 1.5 wt % U^{235} . The fuel slugs were of random (1 to 6-in.) lengths, with a finished OD of 0.4995 ± 0.0005 -in. Each fuel slug was dished on one end to a depth of about 0.005-in., with a spherical radius. These fuel slugs were then loaded into clad-
ding tubes to give a fuel stack length of about 13.6 in. They were loaded according to carbon content to permit post-irradiation evaluation of the influence of

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Figure 10. U-305 A1 Compression Spring and Lower Hardware

Figure 11. U-305 AI Experiment Assembly

carbon chemistry on fission gas release; the loading schedule is given in Table 10. Complete pre-irradiation data for the UC fuel may be found in Reference 7.

The cladding material was SAP containing 5 to 8 wt % Al_2O_3 . The material was extruded into a finned tube geometry, as indicated in Figure 12. The tubes were twisted to give a $90^\circ/\text{ft}$ spiral to the fins to provide rod-to-rod spacing and promote inter-subchannel coolant mixing. The cladding ID was 0.5045 ± 0.0005 in., which yielded a nominal 0.005-in. diametral gap between the fuel and cladding. Complete pre-irradiation data for the cladding may also be found in Reference 7.

TABLE 10
U-305 A1 UC FUEL LOADING SCHEDULE

Bundle Identification and Position in U-305	Fuel Rod Cladding Material	Fuel Column Length (in.)	Number of Fuel Rods per Fuel Compositional Range	Fuel Rod Identification	Fuel Compositional Range (wt % C)
LRA (top)	O = XAP-005	13.6	3	(B)(C)(D)	4.86 to 4.92
			3	(E)(F)(H)	4.94 to 5.06
			3	(J)(K)(L)	4.99 to 5.11
			3	(M)(N)(P)	5.15 to 5.28
	XAP-001		6	R,S,T,W,X,Y	4.90 to 5.07
LSA	O = XAP-005	13.6	3	(B)(C)(D)	4.88 to 4.98
			3	(E)(F)(H)	4.91 to 5.03
			3	J,(K)(L)	4.94 to 5.12
			3	(M)(N)(P)	5.16 to 5.24
	XAP-001		6	R,S,T,W,X,Y	4.90 to 5.13
LTA (bottom)	O = XAP-005	13.6	3	B,C,(D)	4.84 to 5.00
			3	E,F,(H)	4.89 to 5.00
			3	J,K,L	4.90 to 5.12
			3	(M),N,(P)	4.99 to 5.28
	XAP-001		6	R,S,T,W,X,Y	4.88 to 5.05

a) FINNED CLADDING TUBE CROSS-SECTION

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Figure 12. U-305 Test Series SAP Cladding and Fuel Rod Geometry

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Figure 13. Typical SAP-UC Fuel Bundle

The fuel tube closures were formed from 1100 S aluminum end plugs, approximately 3/4-in. long, which were silver-eutectic-bonded to the fuel tube. After the fuel was loaded in the tubes, the final closures were made in a helium atmosphere to improve the heat transfer between the fuel and cladding. A schematic of the assembled fuel rod is shown in Figure 12b.

The fuel rods were then assembled into bundles consisting of 12 rods each, in a circular array around a central dummy cladding tube housing the hanger rod. The end plates were flat 1/16 in. stainless steel, and the fuel rods were attached with a screw and pinned to prevent rotation. The completed fuel bundle was 16-5/8 in. long with a diameter over the fin tips of 3.175 in. $\pm$ 0.005 in., and 3.220 in. $\pm$ 0.002 in. at the spacer rings. A typical SAP-UC fuel bundle is shown in Figure 13.

b. Zircaloy- UO_2 Fuel Bundles

Two Zircaloy UO_2 fuel bundles were used in the U-305 A1 fuel string. Both bundles consisted of fuel rods with six spacer wires attached to the tube wall by spot-welding techniques. The completed spot-welded bundle is shown in Figure 14.

The UO_2 fuel was in the form of cored pellets, each approximately 1/2 in. long, with a core ID of 0.184 in. and a pellet OD of 0.522 in. $\pm$ 0.0005 in. The fuel pellets were dished on one end, similarly to the UC slugs, and were procured to CEND Specification NL-100. The fuel was enriched to 1.12 wt % in the top UO_2 bundle and to 1.52 wt % in the bottom UO_2 bundle. Special solid end-pellets, approximately 3/8 in. long, each of depleted UO_2 , were located on each end of the fuel stack in each rod, yielding an overall stack length of 24.375 in.

The Zircaloy-4 cladding material was procured to the requirements of CEND Specification NL-100. Measured tube ID ranged from 0.521 to 0.534 in., yielding a helium gas bond diametral thickness of 0.009 to 0.012 in. The clearance between the top end-plug and the top of the fuel stack was a nominal 0.160 in. As with the finned SAP cladding, the Zircaloy-4 wire wrap tubing was twisted to give a 90°/ft spiral to the spacer wires to provide rod-to-rod spacing and promote inter-subchannel coolant mixing.

Figure 14. Spot-Welded Wire Wrap Zr-VO₂ Fuel Bundle

3. Description of Other Test Assembly Features

a. Instrumentation

The SAP-UC fuel bundles were instrumented with 19 0.020-in. OD (swaged from 0.040 in.) stainless steel sheathed, grounded junction, Chromel-Alumel thermocouples. The thermocouples were embedded in the fins of selected fuel rods as shown in Figure 15, and were used to monitor the SAP cladding temperatures during irradiation. The thermocouple installation schedule for the three SAP-UC bundles is shown in Figure 16. The Zircaloy-4 - UO_2 bundles were not instrumented.

In addition to the cladding thermocouples, five thermocouples were located in the coolant stream at the interface between the UO_2 and UC bundles. The locations of these thermocouples are also shown in Figure 16. Figure 17 shows a completed bundle assembly including fuel rods, end-plate (outlet end) with spacer ring, cladding TC, and coolant TC.

b. Zirconium Specimens

Zirconium alloy specimens were originally attached to the hanger tube of the U-305 A1 test assembly. The specimens were Zircaloy-4, Zircaloy-2, and Zr-2.5 Nb, which were subjected to various surface treatments to determine relative rates of hydriding and other effects in organic coolant. Figure 18 is a photograph of the specimen installation, and the table in Figure 11 describes the treatment process for each specimen.

B. DESCRIPTION OF THE IRRADIATION FACILITY

The irradiation facility used for the U-305 A1 experiment was the organic cooled U-3 loop of the NRU reactor. This facility is located at the Chalk River National Laboratory (CRNL), Chalk River, Ontario, Canada, which is owned and operated by the Atomic Energy of Canada Limited (AECL).

1. The NRU Reactor

The NRU was originally a 220 Mwt natural uranium fueled, heavy water moderated and cooled reactor. In 1964, the reactor was converted to use fully enriched uranium fuel and it is presently operating near 110 Mwt. In addition to its primary purpose of isotope production, the NRU contains three separate,

Figure 15. Typical Thermocouple Installation in SAP Cladding

Figure 17. Completed SAP-UC Instrumented Fuel Bundle

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Figure 18. Zirconium Specimen Installation

fueled test loops which enjoy a high thermal neutron flux and a high plant factor of about 90%. The reactor utilizes on-line refueling and has the ability to compensate a wide range of flux requirements of the individual loops. This allows the reactor and the loops to run constantly at their maximum power for the duration of an experiment, even though fresh fuel may have been inserted into one of the other loops during the interim. Reference 8 describes the NRU after the 1964 modification.

2. The U-3 Loop

The U-3 test facility is an organic cooled loop with its test section in the E-12 core position (Figure 19) of the NRU. This loop was initially constructed for the purpose of irradiation-testing the WR-1 (Whiteshell Reactor) fuel bundles and pressure tubes. In 1965, the U-3 facility and operational services were contracted on a rental basis by the USAEC for the purposes of providing a suitable irradiation facility for the HWOCR program experiments. The loop is described in detail in Reference 9 and 10, but is discussed herein for orientation with the operational phases of the U-305 A1 experiment.

The loop is of carbon steel construction and, with the exception of the Zircaloy-4 pressure tube, has a maximum rating of a test section outlet temperature of 800°F (427°C) and a pressure of 600 psia. The primary organic coolant rejects heat to the secondary river water coolant through a refluxing-type heat exchanger with a nominal rating of 2 Mw. Table 11 lists the nominal operating conditions of the U-3 loop.

TABLE 11
U-3 LOOP NOMINAL OPERATING CONDITIONS

Heat Rejection (Mw)	1.66
Flow (gpm)	300 (16.5 kg/sec)
Pump Inlet Pressure (psi)	100
Pump Discharge Pressure (psi)	300
Test Section Inlet Temperature (°F)	573 to 680
Test Section Outlet Temperature (°F)	653 to 753
Test Section Outlet Pressure (psi)	200
Coolant Type	Santowax OM + 10 to 30% HB HB-40 + 22 to 33% HB

SOUTH

A B C D E F G H J K L M N O P Q R S

CR

Figure 19. NRU Core Map

The U-3 loop is illustrated schematically in Figure 20. The loop consists of three primary subsystems. These are the main loop, the degassifier system, and the purification system. The characteristics and purposes of each of these subsystems are as subsequently described.

a. Main Loop

The main loop provides the circulating coolant at controlled temperature and flow rate for use in the test section. The operation of the main loop circuit under normal U-305 A1 conditions is described in the following paragraphs.

The organic coolant is continuously circulated by two of the three main pumps. The third pump remains on standby and is automatically started when another pump fails or a loop trip occurs. The coolant discharged from the pumps passes directly to the test section where it is used as a heat transfer and transport medium for the thermal energy generated by the fuel string.

Coolant flow rate control is provided in the test section outlet piping by an orifice plate sensing element in conjunction with a throttling valve. The coolant temperature regulation system is downstream from the throttling valve. A flow diverter valve is used to partially bypass coolant around the main loop cooler, as required to maintain the test section inlet temperature constant. The loop cooler is a refluxing shell-type cooler in which the organic stream loses heat by boiling the water in the shell which in turn gives up heat by condensing on tubes containing the secondary river water coolant.

The surge tank is downstream of the loop cooler, and is used to provide a constant inlet pressure to the pumps and for coolant level control. Pressurization is provided by a bottled nitrogen supply and a vent system. The surge tank liquid level is controlled by using the dump tank as a liquid source or sink as required.

Electrical resistance heaters are incorporated in the main loop to maintain the coolant at desired temperatures during non-nuclear operation. They are positioned between the flow orifice and the flow control valve, and are not bypassed during nuclear operation. Another special component associated with the main loop is the water addition system. This system provides a means of maintaining a water concentration in the coolant up to approximately 1000 ppm. The system consists of a distilled water source and a variable capacity positive displacement pump.

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Figure 20. Simplified U-3 Loop Schematic

The portion of piping that passes through the reactor is a special pressure vessel (the pressure tube) that completely isolates the loop from the reactor. The present pressure tube is constructed of Zircaloy-4 with a 3.25 in. ID and a length of approximately 30 feet. The U-3 pressure tube is separated from the NRU D₂O moderator by a CO₂ annulus and a Zircaloy-2 calandria tube. The design operating pressure for this pressure tube is 335 psi at 750°F.

b. Degasification System

A degasification system was installed on the U-3 loop to remove the non-condensable gases from the main loop coolant. This is necessary to maintain the coolant vapor pressure below the saturation point at the test section discharge. The degasification system also provides a flow of coolant to the dump tank which is used for level control in the surge tank.

The degasification system operates in the following manner: A sidestream is withdrawn from the main loop downstream of the flow control valve and fed to the degasifier tank. The pressure is adjusted so that about 10% of the feed steam is flashed to vapor. The vapor stream, composed of noncondensable and low boiling vapors, flows into two condensers, where reusable coolant is condensed and returned to the main loop. The resulting vapor stream then enters two cold traps where water and undesirable light ends are collected and discharged into the waste system. The resulting noncondensable gases are then vented up the wastegas stack. The degassed coolant and the condensed coolant are fed to the dump tank and returned to the main loop.

The nominal operating conditions of the degasifier system during U-305 A1 operation were as follows:

Degas feed flow (gpm)	5
Feed pressure (psia)	110
Feed temperature* (°F)	650 to 750
Degas tank pressure (psia)	30 to 50
Degas tank temperature (°F)	565 to 720
Percent of feed flashed	~ 10
Noncondensable discharge flow	0.5 to 1 ft ³ /hr at 45 psi and 212°F

*Same as test section outlet.

c. Purification System

The purpose of the purification system is to remove gross particulate matter and fouling-producing species from the organic coolant. During normal operation, a 10 gpm side stream from the main loop pump discharge is fed into two absorption columns which may be connected either in parallel or in series. These columns use 200 lb of 30/60 mesh LVM grade attapulugus clay. No additional activation of the clay is necessary prior to its use. The purification stream enters two glass fiber filters with 1- μ porosity. The clean organic stream is then returned to the main loop.

A heater is provided on the inlet to the system to maintain the purification stream at about 650°F. A small chlorine removal column had been installed in the loop, but experience during the U-305 experiment had shown that chlorine could easily be removed with attapulugus clay and the chlorine removal column was therefore never used during the U-305 A1 experiment. In fact, it was removed when the coolant was changed to HB-40. Chlorine was never a problem in either the U-305 or U-305 A1 experiment and should never be a problem in an organic cooled reactor as long as care is taken to prevent its introduction into the system.

d. Experiment Data System

The U-305 A1 experiment data system included the experiment instrumentation and control system, the data collection system, and the data reduction system.

(1) Experiment Instrumentation

The experiment instrumentation and control system utilized primary two-signal sources — the loop and the fuel string. Figure 20 schematically shows the features of the main loop instrumentation as it existed at the onset of the irradiation. Resistance temperature detectors are provided for accurate inlet and outlet test section temperature measurements.

Test section inlet and outlet pressures are monitored, as are other pressures around the loop. A differential pressure cell, designated dp-2, was positioned across the test section to detect changes in the hydraulic performance of the fuel string. The main loop flow was measured with an orifice plate utilizing three differential pressures (dp) cells in parallel to determine the pressure drop

across the orifice. The signal from one dp cell is used to control the flow; the signal from the second is monitored by the data logger; and the third instrument is a recorded backup.

During November 1966, two new differential pressure cells (dp-81 and dp-82) and two new absolute pressure transducers (PI 79 and PI 80) were added to the loop instrumentation to provide more accurate and reliable pressure information. Also, the existing flow transmitters were moved to a cooler location and their associated piping runs re-engineered. The original differential pressure transducer (dp-2) was removed in December 1966.

Nuclear instrumentation on the U-3 loop included two coolant gamma activity monitors, which are positioned downstream of the test section, and five neutron flux monitors positioned on the outside of the pressure tube. These flux monitors are of the vanadium beta-emitter type and are approximately 8 ft long. Each flux monitor is wrapped around the pressure tube at an elevation corresponding to the mid-point of one of the U-305 A1 bundles. A suitable mv signal is obtained by measuring the voltage drop across the 10-k Ω resistor in the circuit.

The U-305 A1 fuel string was instrumented with 24 thermocouples. The type and placement of these TC's were described in Section III and are shown in Figure 16. These thermocouples were operated with a 100°C reference junction, and were monitored on both the data logger and recorders.

The loop instrumentation also provided alarm and trip functions in the event of loop operation outside prescribed limits. The instrumentation is capable of initiating two types of trips — a loop-only trip and a reactor trip. The loop-only trip results in full cooling by diverting all coolant into the loop cooler and results in maximum flow by starting the third main pump and opening the flow control valve. Selected instruments are used to indicate these under conditions of low flow, low pressure, low liquid level, high temperature, main pump failure, and fire. During the operation of the U-305 A1 experiment, the limits were adjusted so that the reactor trip would be initiated prior to the loop trip.

(2) The Data Collection System

The data collection system consisted of a sophisticated data logger and computer system, in conjunction with the hand recorded data readout from meters,

gages, and strip chart recorders. The manual logging of data was done by the loop operators, either once an hour or once a shift, depending on the importance of the data. There "loop logs" were an important source of information to assist in analyzing experiment behavior.

The REDACE automatic data collection system used for the NRU and NRX loops was used to log data for the U-305 A1 experiment. The system utilizes a multiplexing input; analog to digital conversion; magnetic core memory; and computerized conversion with a punched paper tape, magnetic tape and type-writer output. Simply, this system obtains the input signals either on demand or at a preset interval, converts them to digital engineering units and presents them on a typewriter listing. The unit performs a data scan in less than 1 sec and can take and calculate repetitive scans every 5 sec. For the U-305 A1 collection, 30-min scans were usually taken and output on the typewriter. The typewriter output was used as the primary source of immediate data for the U-305 A1 experiment operation. The magnetic tape generated by REDACE was run on the G-20 computer at CRNL so that the data pertaining to only the U-3 loop could be extracted and placed on punched cards. There were then shipped to AI where further data reduction was performed.⁽¹¹⁾

The complete data acquisition system is schematically illustrated in Figure 21. The two types of data procurement (REDACE and manual) were used to assemble the operational data.

Figure 21. U-305 A1 Data Acquisition System

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