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Quarterly Status Report of LASL Rover Program

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For The Atomic Energy Commission

(Title Unclassified)

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I. PHOEBUS-1

PHOEBUS-1A

Introduction

The Phoebus-1A full power test was conducted on June 25, 1965 at the NRDS. The reactor was held at full design power and temperature for approximately $10\frac{1}{2}$ min before an unexpected loss of coolant resulted in core support overheating and subsequent ejection of core parts through the nozzle. This of course cancelled the planned restarts in which temperature would have been controlled without an inner log power control loop. Preliminary analysis of the Phoebus-1A run data indicates, however, that the new temperature control scheme should work well and it will be used on future reactors.

Full Power Run

Startup

The major variables (flow rate, power, and Station 20 core material temperature) were very close to predicted profiles during the startup, as shown in Figs. 1, 2, and 3. Measured flow rate was very close to desired (Fig. 1) except at the earlier times. At these times, however, the flow rate demand had been advanced 2 sec in an attempt to account for the flow controller lag (velocity error in the flow controller) and line dynamics so that the reactor flow rate profile could be obtained relative to the other profiles.

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Fig. 1. Measured flow rates during startup in Phoebus-1A test.
 Fig. 2. Measured (neutronic) power during startup in Phoebus-1A test.

Fig. 3. Nozzle chamber temperature during startup in Phoebus-1A test.

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The measured power (Fig. 2) lagged the demand by approximately 1 sec during both the first and second ramps. This lag could be a combination of the power controller velocity error and program inaccuracies. However, both the measured power and flow rate are well within accepted accuracies.

The nozzle chamber temperature (Fig. 3) was generally lower during the initial startup phase (first 25 sec) than predicted. As seen in Fig. 1, the indicated flow rate was higher than the desired flow rate for about the first 40 sec.

The recorded control drum angle correlated very well with predictions during the startup; the variation was always less than 4° ($\sim 25\%$). This satisfactory agreement gives confidence in the success of the planned use of a new temperature control scheme which would contain an inner log power control loop.

Full Power Hold

Following the 45-sec intermediate hold and the second power ramp, the full power hold was reached at 22559 digital time. Thermal power, coolant flow rate, and nozzle chamber temperature peaked just prior to the first (of four) selected steady-state time (22600) as shown in Figs. 4, 5, and 6. The power and temperature decreased slowly but steadily throughout the run, the power from 1090 to 1050 MW and the temperature from 4150 to 4030 $^{\circ}$ R. A possible cause of the decrease could be a drift of the Station 20 thermocouple temperature-to-voltage calibration (about 100 $^{\circ}$ R in the upward direction) but furnace tests of thermocouples since the run have failed to show such drifts.

Just prior to the beginning of the intermediate power hold (22467 sec), a leak (and small fire) occurred in the propellant system of the reactor/test car complex. Postrun investigation showed the leak source to be a crack in the weld between the clamp ring and the fitting boss. Radiographs of the area showed an inadequate root penetration of this weld.

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Fig. 4. Thermal power in Phoebus-1A test.

Fig. 5. Coolant flow rate in Phoebus-1A test.

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Fig. 6. Nozzle chamber temperature in Phoebus-1A test.

Four transfer function experiments were performed during the full power hold. They were: (1) a small step downward in temperature demand, followed by an upward step to the original value; (2) a sine wave transfer function measurement of the closed flow rate control system; (3) a pseudo-random noise input to flow rate and pump speed demands; and (4) a pseudo-random noise input to temperature demand. The results of the flow rate and pump speed demand tests are given below. Data on the other tests have not yet been analyzed.

A malfunction of the Dewar B liquid level instrumentation resulted in a loss of LH_2 flow just as the reactor was beginning the ramp down from full power. The level indication was 27% when the dewar ran dry at time 23192 sec. The reactor was scrambled by the pump overspeed trip at 23195 sec, which was a second or two later than expected. Figure 7 shows time profiles of some of the more important parameters during this event. A further discussion of the level indication problem and its consequences is given later in this report (see Part III, p. 41 et seq.).

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Fig. 7. Variation of parameters in Phoebus-1A during ramp down from full power.

Consequently, the sudden loss of coolant resulted in extreme overheating of the tie rods, extensive core damage, and ejection of core material out of the nozzle.

Cooldown

Due to the excessive heating and depleted coolant supply, cooldown procedures were altered radically. The cooldown program subsequently used was concerned only with maintaining reactor temperatures below those which would cause further catastrophic failure of portions of the reactor internal structure.

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The automatic control system is arranged so that, when a flow shutdown occurs, the LH₂ pump is isolated from the reactor by closing ACV-16 (the main LH₂ flow valve) and GH₂ is then programmed through the reactor. Pressure upstream at the gas venturi is programmed to 0.6 P_d, where P_d is the pump discharge pressure, in 2 sec at the time of shutdown and to 1.2 P_d in 5 sec. This should provide LH₂ coolant at ~ 40 lb/sec for 2 sec, followed by increasing GH₂ flow from 11 to 17 lb/sec at the end of 5 sec. The technique failed to work properly on Phoebus-1A primarily because pump discharge pressure had dropped to 275 psi when the flow shutdown occurred.

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Results

Despite the damage sustained by the reactor, the preliminary data review indicated successful operation in several significant areas.

1. The startup profiles were very close to those planned. The flow "bobble" which occurred during the Kiwi-B-4E startup was significantly decreased by the new profiles.
2. Predicted and measured control rod positions during startup agreed very well. This strongly supports the proposed scheme of closing the temperature control loop on control drum position instead of the present closure on power.
3. The run profiles were extremely close to those planned. The major parameters were essentially identical with the predicted values.
4. All control systems operated as expected. Noise, oscillation, and step input experiments on the control systems were successfully completed and the data appear to be excellent.

Phoebus-1A Data Analysis

Steady-State

The detailed comparisons of the calculated and measured steady-state thermal and flow performance of the Phoebus-1A reactor are continuing. The more significant results of the preliminary data analysis are summarized below. A detailed report (LA-3375-MS) will be issued shortly.

In the preceding Quarterly Status Report (LA-3341-MS), the prerun predicted values of the major flow and thermal parameters for the planned intermediate and full power hold conditions were given (pp. 12, 13). In Tables 1 and 2 these predictions are repeated together with the values of the same quantities measured during the holds for Phoebus-1A. It is clear that the major parameters of power, flow rate, and (mean) fuel element exit H_2 temperature were satisfyingly close to those planned.

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Table 1. Comparison of Prerun Predicted and Measured Steady-State Thermal Performance Intermediate Hold (22510 sec)

Component	Inlet Temp, °R		ΔT, °R		Inlet Press., psia		ΔP, psi		Flow Rate, lb/sec		Power, MW	
	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.
Nozzle Coolant	49	52	65	56	648	598	140	109 ^(a)	58.0	--	--	--
Reflector	114	108	34	41	508	489	37	27 ^(a)	60.0	59.1	8	8.0*
Flow Separator	148	149	--	--	471	461	12	9 ^(a)	60.0	59.1	--	--
Core	148	149	Outlet Temp, °R		459	454	67	72 ^(b)	60.0	59.1	633	604*
			Pred.	Meas.								
Fuel (mean)			3100	3060	--	--	--	--	54.9	53.3	625	595*
Support			560	657 ^(b)	--	--	--	--	3.0	3.3*	5	7*
Periphery			550	425*	--	--	--	--	2.1	2.5*	3	2.7*
Tubes			680	520	--	--	--	--	0.9	1.1*	--	--
Cavity			450	352*	--	--	--	--	1.2	1.4*	--	--
Nozzle Chamber	2900	2835*	--	--	392	381	--	--	60.0	59.1	--	--
Total System	--	--	--	--	--	--	256	217	--	--	641	612
Mean Core Thermocouple Temp., Station 20, °R	Pred.	Meas.										
	2000	1952*										

* Quantities derived from measured data.

(a),(b) Significant discrepancies; see text.

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Table 2. Comparison of Prerun Predicted and Measured Steady-State Thermal Performance Full Power Hold (22600 sec)

Component	Inlet Temp, °R		ΔT, °R		Inlet Press, psia		ΔP, psi		Flow Rate, lb/sec		Power, MW	
	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.
Nozzle Coolant	54	56	122	104	975	894	238	186 ^(a)	68	--	--	--
Reflector	176	160	53	58	737	708	52	45 ^(a)	70	69.3	15	15.5*
Flow Separator	229	218	--	--	685	663	18	13 ^(a)	70	69.3	--	--
Core												
	229	218	Outlet Temp, °R		667	650	110	102 ^(b)	70	69.3	1110	1081 *
Fuel (mean)	↓	↓	4500	4460					63.5	62.2	1098	1066 *
Support			685	887 ^(b)					4.0	4.3 *	7	11 *
Periphery			820	614*					2.5	2.8 *	5	4.4*
Tubes			940	752					1.1	1.2 *		
Cavity	↓	↓	725	515*					1.4	1.7 *		
Nozzle Chamber	4200	4150*			557	548			70	69.3		
Total System							418	346			1125	1097
Mean Core Thermocouple Temp., Sta. 20, °R	Pred.	Meas.										
	3060	3001										

* Quantities derived from measured data.

(a), (b) Significant discrepancies; see text.

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There was a slight downward drift during the full power hold (see Figs. 4, 5, and 6). This is typified by the thermal power decrease of about 40 MW ($\sim 4\%$), which is essentially verified by the neutronic power data. A similar phenomenon was observed from the Kiwi-B-4E data (LA-3185-MS). The cause of the decrease is still under study. For this purpose it will be necessary to use more refined data to evaluate such small percentage changes.

Several of the predicted reactor component pressure drops are too high when compared with the measured values (indicated as (a) in Tables 1 and 2). The data for the reflector and nozzle systems are typical. This discrepancy remains even after the calculated pressure drops are adjusted for the measured temperature and pressure conditions. The reason for these differences has not yet been determined although a portion of the discrepancy for the nozzle coolant is due to the too high prediction of heat pickup. The heat pickup for the reflector system, on the other hand, is quite close to the calculated value.

The lower measured than computed pressure drop (ΔP) for the flow separator is particularly puzzling. For the Kiwi-B-4E Gas Cold Flow and Full Power runs, the flow separator ΔP was found to be a closely calculable function of the flow rate and core inlet fluid density. The same type of relationship was expected to hold for the very similar component in Phoebus-1A. Results for the GN_2 flow checks of Phoebus-1A (Gas Pass, EP-II and EP-III) did yield a very similar flow separator flow ΔP calibration. However, the ΔP recorded during the full power run was consistently and considerably less than ($\sim 2/3$) that which would have been calculated using the Gas Flow calibration. Post-test examinations have not shown any damage to the flow separator or any other discrepancy which would account for the low measured ΔP .

Another very significant discrepancy is noted as (b) in Tables 1 and 2. The difference between the full power measured mean core support tie rod coolant exit H_2 temperature (887°R) and that predicted (685°R) implies an error of about 32% in the ΔT and therefore a considerable

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underestimation of the heat load to this coolant. When the calculations were adjusted for the actual run conditions, the exit temperature was decreased even further ($\sim 25^{\circ}\text{R}$ at full power). Detailed studies of the analytical model (method described in LA-3341-MS, pp. 10-14 and LA-3170-MS) used to perform these calculations are underway. Initial indications are that the calculated tie rod coolant exit temperatures can be considerably improved. This is achieved principally by decreasing the thermal resistance of the pyrographite insulating sleeve by use of more recent (higher) thermal conductivity data and dividing the radial representation of the pyrographite into three regions which yields a better estimate of the conductance of the sleeve. Similar low values of calculated support channel exit temperatures were noted for the Kiwi-B-4E (LA-3185-MS, Chap. IX). However, it was concluded at that time that the data were primarily at fault. The Phoebus-1A results are considered to be valid because of an improved instrumentation installation technique. Recalculation on Kiwi-B-4E confirm the improvements in the model and also indicate that the data were valid. The agreement between measured and calculated core ΔP 's has also been improved by the modifications made to the analytical model.

The temperature data recorded during the Phoebus-1A full power hold give some indication that there may have been an azimuthal thermal asymmetry present. The magnitude of asymmetry is difficult to infer since the instrumentation angular coverage was not extensive (for thermocouple locations see LA-3212-MS, pp. 23-27). The data hint at a minimum or dip in the temperatures in the region roughly of $\theta = 0^{\circ}$. Such an asymmetry (if it existed) was in direct contrast to the Kiwi-B-4E experience where both post-test fission distribution data and recorded temperature data indicated the absence of any detectable asymmetry. The resolution of the matter for Phoebus-1A will perhaps come from the post-test determination of the core fission distribution. Of particular interest will be the data for the NbC-coated sector (030) which may have perturbed the fission distribution in this region.

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Fig. 8. Observed and calculated axial temperatures in Phoebus-1A.

Fig. 9. Observed radial temperature variation at Station 20 in Phoebus-1A.

The detailed analysis of the core temperature data recorded during the steady-state power holds will not be completed until the core power density distributions are available from the post-test determinations of the fission distribution. The thermocouple readings have been compared with pre-test predictions. The axial variation of the data (at 22600 sec) is compared in Fig. 8 with a predicted profile of the mean fuel element maximum material temperature. The familiar high-temperature shunting of the thermocouple signals near the core exit end is evident. Although the data generally appear to lie above the predicted curve, this may be partially a result of the suspected asymmetry. The axial data are from five different partial lines located in central support elements of the D-1 clusters. The agreement may possibly improve with comparisons that use actual run data of power, flow rate, pressure, etc., and consider the temperatures of the unloaded support elements.

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The radial temperature survey in the core was covered by one main radial line at Station 20. The thermocouple data for full power are summarized in Fig. 9. No predictions are included but the radial variations can be contrasted with the fuel element temperature plot in Fig. 6 of the preceding Quarterly Report (LA-3341-MS, p. 14). The following preliminary observations can be made. Qualitatively, the predicted peak at a radius of 4 in. is reproduced, but the temperature in the 00 cluster was unexpectedly high. The drop in temperature of $\sim 280^{\circ}\text{R}$ between radii of 8.3 and 14.3 in. was not as predicted; the continued drop beyond radius 14.3 in. may be due to a power density (fission) reduction caused by the control drums being farther in than assumed in the fuel element orificing (flow balancing) recipe. Furthermore, the filler elements were about 150°R hotter than nearby center elements. The quantitative evaluation of these features of the data will require comparison with detailed calculations planned when the complete post-test data are available.

Shutdown

Comparison of the planned shutdown profiles (LA-3341-MS, pp. 17-19) with the data are obviously not possible due to the emergency shutdown imposed.

Phoebus-1A Disassembly

Introduction

The Phoebus-1A reactor was brought into the R-MAD building on August 9, 1965, and normal disassembly procedures were followed in removing the reactor from the test car. Disassembly was completed on August 26, 1965.

Damage

The loss of coolant at the termination of the reactor run resulted in considerable melting of core metallic components and expulsion

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and damage to a major portion of the elements in the central portion of the core. Nearly all the regular support blocks were expelled. The melted material covered the support blocks remaining in the core and approximately 3 in. of the element hot end, fusing that portion of the core into a solid piece. Disassembly of the fused portion was accomplished by grinding off the element hot ends at Station 49, thus freeing the remaining length of the elements.

Loose elements in the central portion of the core were removed individually, many as full length fuel elements. Some full length tie rods were found but the button on the tie-rod end had broken off in what appeared to be a cold fracture break.

Considerable amounts of debris had fallen into the flow separator screen in the dome assembly, thus making it impossible to get meaningful results by detailed visual examination. Although no damage was noted to the reflector cylinder itself, some of the leaf springs were discolored and the Al parts used to orient the leaf spring showed signs of overheating.

A crack was noted in the weld used to attach the manifold to the clamp band. Subsequent inspection revealed a considerable leak through the weld crack.

Examination of Core

The core was moved to the upper disassembly bay on August 13 and the reflector cylinder slit in the normal manner. Most parts of the wrapper were tightly fused together but the wrapper itself was not fused to any other components. No damage was noted to the slats and pyrotils.

An attempt was made to evaluate the periphery on each of the six sectors. This evaluation has not yet been completed, but the following observations can be made:

1. Corrosion of the 030 sector (completely NbC coated) was practically nonexistent.

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2. Corrosion to the filler elements in the 210 (circular) sector was rather severe. Little or no corrosion was noted in the underlying elements.

3. Corrosion to peripheral uncoated 16-hole elements in other sectors exposed the bore coatings in many cases at tile joints. However, on the periphery of two sectors the 16-hole elements were coated with NbC and these did not exhibit corrosion at tile joints.

4. Corrosion to peripheral uncoated filler elements was noticeable at tile joints and appeared uniform around the core periphery.

A more detailed report of peripheral corrosion will be available when films of the various components have been studied.

To aid in the evaluation of various core components, photographs were taken of all identifiable core components. The fuel element and center unloaded elements had all six faces (as well as the hot end) photographed, using the new automatic photo system installed in the upper disassembly bay.

Fuel Elements

A superficial examination of randomly-selected fuel elements during the course of disassembly showed several obvious features of corrosion behavior. The detailed effects will be determined as completely as possible under the circumstances from the disassembly photographs and postmortem examination of individual fuel elements. The obvious features were as follows:

1. Almost the entire hot end of the core was fused together except for portions of the badly disrupted central part which extended radially to about the F and G clusters.

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2. The hot ends of those elements which could be observed in the disrupted portion or from breaking and cutting operations appeared to have suffered very little corrosion. There were only a few cases of verified corrosion in the vicinity of the glued joint and step or taper tips. Many glued joints were broken and exposed with little or no detectable corrosion.

3. Some external pinholes were noted but no detailed count or correlation of occurrence with position can be attempted until the photographs are analyzed. The occurrence will then be correlated with core position and with the tendency to pinhole of sister elements in the same coating batch.

4. There was a curious cracking and element corner break-out on many elements in the external NbC-coated sector 030. The graphite in these broken areas did not seem normal but the peculiar appearance was evidently not due to corrosion. The effect will be examined further during the post-mortem investigation.

5. Except for the external pyrocarbon (PyC) coated sector 150, the external surface streaking appeared to be normal, i.e., streak corrosion followed downstream by streak deposits of soot and PyC which commonly overlapped. In sector 150, the PyC streaks were often farther downstream and separated from the sooty deposit.

6. The tab-tipped elements appeared to be in good condition as far as they could be observed. A few of the tips were salvaged for further investigation.

7. There were no obvious features, either good or bad, concerning the MoS₂-coated elements in sector 330. A selected number of these will be examined in greater detail.

8. No examination was made of the interior of elements during the disassembly procedure. This will be done on a selected number during the postmortem operation.

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Fuel Element Photocoverage

The simplified photographic system installed by LASL and ACFI for use during NRX-A3 disassembly was used during that disassembly and performed admirably. Upon receipt of the first prints WANL ceased visual inspection of the elements in favor of inspection of the photographs.

The photographic system for Phoebus-1A disassembly was installed and used. The results are as good or better than those obtained during NRX-A3 disassembly. Although the photographic components gave trouble through the last 60% of disassembly and prevented taking all the data desired, built-in redundancy allowed all data to be recovered and used. Altogether, the photographic system was considered to be satisfactory.

Phoebus-1A Instrumentation

Experimental Core Thermocouples

There were 19 experimental core thermocouples in Phoebus-1A with the following enlarged geometry: 0.110-in. o.d. Ta sheaths, 0.020-in. diam W and W/W-26% Re wires, and fired BeO insulator beads. All but two were coated with liquid moly MV grease; one had an ungrounded junction, and another had a 5-mil coating of vapor-deposited W over the Ta sheath. Operational behavior is given in Table 3. The cause of the failures at Station 38 is not known. There appears to be less shunt error at Station 32 than was found with the standard 1/16-in. diam thermocouple. There is evidence of shunt loss at Station 44.

Exit-Gas Thermocouples

Four W/W-26% Re thermocouples were located in the core exit plenum (nozzle chamber). Two of these were brought through the core in dummy unloaded fuel elements in the central cluster. The thermocouples projected ~ 8 in. into the plenum. They were enclosed in cooling jackets which extended to within 3/4 in. of the thermocouple junction. Thus, the

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Table 3. Experimental Thermocouple Performance

<u>Station</u>	<u>Number</u>	<u>Comment</u>
20	2	Steady operation, reading somewhat high because of temperature asymmetry in the core.
26	3	One satisfactory; one scaled too high; one drifted upward by $\sim 250^{\circ}\text{R}$ during the run.
32	3	Two satisfactory, gave $\sim 200^{\circ}\text{R}$ higher reading than standard 0.062-in. o.d. thermocouples; one failed open at start of high power hold.
38	6	One steady; five showed large drifts up or down during run.
44	5	All essentially steady but $\sim 350^{\circ}\text{R}$ spread in readings.

thermocouples were cooled through all but ~ 1 in. of their length. Previous calculations had shown that, under these conditions, the shunt error should be very small. As far as can be determined at this time, the thermocouples indicated the correct core exit gas temperature throughout the high power hold. The two thermocouples which were brought through core peripheral cooling holes were damaged during assembly and did not function during the run.

Experimental Thermopiles

Two experimental Cu/Constantan thermopiles were installed in Phoebus-1A in order to make accurate measurements at low fluid temperatures. One sensor (centered in the core inlet plenum) consisted of four junctions (one of the original five was damaged) and the other sensor (installed through the pressure vessel into the reflector inlet plenum) consisted of five junctions housed in a standard Pt probe cage. The reference in each case consisted of the appropriate number of junctions housed in a similar cage installed in the nozzle cooling inlet manifold. All junctions had the bare wires exposed to the H_2 stream.

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The core inlet measurements agreed to within less than 1°R with the average of the regular thermocouple readings made in the plenum. The reflector inlet plenum measurements are 20 to 37°R less than other measurements made at different azimuthal locations. However, this could be due to a known asymmetry. An indication of the fast response of the bare junctions was obtained during the shutdown when a 7 cps flow and pressure oscillation showed up clearly on both thermopile records.

It is felt that both thermopiles functioned properly and that the resultant low temperature measurements are probably the most accurate records for these plenums which have yet been made.

Copper-Constantan Lead Wire Experiment

A facility experiment was performed during the Phoebus-1A test to measure the error introduced into Cu/Con thermocouple channels by the use of Cu and Constantan lead wire procured from different sources. Two test couples were connected as a thermopile and placed in a LN_2 dewar in the privy. They were referenced to a two-element thermopile in the reference LN_2 dewar in the test cell through the standard car, plug, and test cell wiring. The difference voltage, which should have remained zero, was recorded.

At the beginning of the full power run, the channel had a $100\text{-}\mu\text{V}$ offset, but during the rise to full power, it increased by approximately $15\text{ }\mu\text{V}$. Such an offset amounts to 5 to 6°R around LN_2 temperature and to 10 to 12°R in the 50 to 70°R region. This type of error has not been measured or corrected to date.

Instrumentation Connectors

Six electrical connectors were placed in the core inlet plenum as an experiment prior to their general use for instrumentation leads in Phoebus-1B. Four were installed as eventually intended, to connect swaged Cu extension leads to W/W-26% Re core thermocouple leads. The remaining

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two were instrumented with thermocouples to measure their internal temperatures. All six channels worked well during the Phoebus-1A test. The internal temperatures were below 420°R during the full power hold, and they rose to a maximum of 610°R during the cooldown.

Pressure-To-Pressure Transfer Functions

During the Phoebus-1A full power test, a pseudo-random signal was fed into the flow demand and, with pre-emphasis, into the rpm demand. The pre-emphasis filter was used to obtain a relatively flat noise signal on pump exit pressure. The experiment was only partially successful because the specific speed loop was in operation and there was a small amount of bypass flow through ACV-2. This may influence the pipeline pressure-to-pressure transfer function.

The data for other pressure-to-pressure transfer functions throughout the nozzle and reactor have not been analyzed but appear to be good. Digital analysis is in progress.

Other Phoebus-1A Results

The various experimental plans carried out in connection with Phoebus-1A and observations made during the full-power run are described in the section on NRDS Activities (p.47 et seq.)

PHOEBUS-1B

Introduction

Phoebus-1B is a reactor very similar to Phoebus-1A but modified to run at a higher power so that the fuel elements will experience thermal stresses similar to those expected in the Phoebus-2A reactor. The following changes have been made in the Phoebus-1B planning: (1) additional experiments have been added as a result of the Phoebus-1A test observations;

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(2) the reactor will not be tested until Test Cell C modifications are complete; and (3) the reactor will be assembled in Kiva 3 and accurate fission distributions measured before shipment to NRDS. Changes (2) and (3) require a delay in the Phoebus-1B schedule. At the present time, it is expected that the reactor will arrive at Test Cell C about the middle of June, 1966. It is possible that the full-power run will be closer to 1600 MW than the 2000 MW previously contemplated (see p.27).

Status

Detail drawings have been released for the fabrication of all major components except the tie tube support structure. The design of these components has been completed and the detailed drawings are being made.

The preliminary observations of Phoebus-1A core elements have led to a decision to incorporate several combinations of NbC-coated elements in the Phoebus-1B periphery. These will include coated fuel and filler elements in various combinations.

One group of tab-tipped elements will be included in the Phoebus-1B core. The group will consist of seven regular clusters, all grouped together near the center of one sector.

Design and Analysis

Core performance calculations have been made using the ~~OPTIØN~~ cluster model which gave the best agreement with Phoebus-1A measurements. A reference design was used with a tie rod channel hydraulic diameter of 90 mils. This results in a tie-rod coolant outlet temperature of 507°R with 9.3% of the cluster flow bypassed to the support channel. Preliminary results indicate some increase in the 166 psi core ΔP . Further calculations are being made to determine these ΔP characteristics more accurately.

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Periphery calculations for the reference four-seal design give a slat coolant outlet temperature of 832°R with 3 lb/sec flow and a core pressure drop of 192 psi.

Maximum perimeter filler and reflector cylinder temperatures have been calculated assuming no cavity coolant flow. The results indicate that filler material temperatures do not differ significantly between a normal four-seal cavity and a stagnant cavity. The corresponding reflector cylinder temperatures, however, differ by approximately 600°R . Calculations are under way to determine cavity coolant outlet temperature and cavity pressure as a function of radial pin leakage and graphite permeability.

Instrumentation

The Phoebus-1B reactor instrumentation as presently planned requires the following types of channels:

Cu/Con thermocouple	= 73 channels*
Chromel/alumel thermocouple	= 82 "
W/W-26% Re thermocouple	= 107 "
Strain gauge	= 34 "
Displacement transducer (strain gauge)	= 14 "
Displacement transducer (LVDT)	= 4 "
Platinum resistance probe	= 12 "
Pressure transducer	= 39 "
Vibration transducer	= 4 "

* Includes 10 channels for the two Cu/Con thermopiles.

Additional channels will be required for experiments external to the reactor but these needs have not yet been defined.

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Nominal Fuel Element Elastic Thermal Stresses

Calculations were completed to evaluate the nominal fuel element thermal stresses (cf. LA-3280-MS, pp. 116-117 and LA-3341-MS, pp. 32-34) for the current Phoebus-1B design operating conditions. The stresses of interest were those associated with removal of the generated heat by the H₂ coolant. The reactor operating conditions used were as follows:

Power	= 2000 MW
Flow Rate	= 123 lb/sec
Fuel Exit H ₂ Temperature	= 4600°R

The fuel element properties used were intended to be representative of ~ 450 mg/cm³ bead loaded elements. The fuel element geometry assumed the current nominal dimensions (hole locations and flat-to-flat of the hexagon) and a coolant hole diam of 0.096 in. The interaction effects of the NbC bore coating and inelastic material behavior were neglected in the analysis.

The results obtained are illustrated in Figs. 10 and 11. Figure 10 is a plot of the axial variation of the thermal stress components at the surface of the outer coolant hole in the center of the flat. The axial stress component (σ_z) was found to be a maximum toward the outer boundary of the element, whereas the in-plane component (σ_t) maximum occurred diametrically opposite for this coolant hole. The maximum values of both stresses occurred at about 26 in. from the core inlet, slightly downstream from the location of the peak power density. The isostress plot of the principal value (maximum tensile stress) of the in-plane thermal stress, shown in Fig. 11, illustrates the local nature of the stress distribution and large stress gradients adjacent to the coolant holes. The magnitudes of the stress values are essentially double those calculated for the Kiwi reactors and for the fuel elements in Phoebus-1A.

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Fig. 10. Calculated axial variation of Phoebus-1B fuel element thermal stress.

Fig. 11. Isostress plot for in-plane component of thermal stress.

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Comparison of Phoebus-1B and -2A Fuel Element Thermal Stresses

A preliminary analytical study was completed comparing the calculated elastic thermal stresses expected for the fuel elements in the Phoebus-1B and Phoebus-2A cores. The principal significant differences in the thermal stress conditions of the two reactors are given in Table 4.

Table 4. Calculated Fuel Element Thermal Stresses

<u>Quantity</u>	<u>Phoebus-1A</u>	<u>Phoebus-2A</u>
Power, MW	2000*	5000
Flow Rate, lb/sec	123*	285
Fuel Exit H ₂ Temp., °R	4600	4600
Coolant hole Diam., in.	0.096	0.110
Hole Location	Standard	Variable
Power Density, ** BTU/in ³ -sec	87.8*	100

* These quantities were treated as variable parameters.

** Maximum value axially in the core.

The same thermophysical and mechanical properties were used for the fueled material in both cases. The locations of the 0.110-in. diam coolant holes in the Phoebus-2A elements were varied (as was done in a previous analysis, LA-3341-MS, pp. 32-34). A major objective of the study was to indicate the power level for the Phoebus-1B reactor core which would yield the same thermal stresses expected for Phoebus-2A. The results are summarized in Fig. 12. The Phoebus-1B power which will give the same in-plane stress for the two cores is plotted with the Phoebus-2A hole locations as parameters (see the reference given above for the influence of hole location variations on stresses). Similar results were also obtained for the matching of the axial thermal stresses in the two reactors. It appears that if Phoebus-1B is run at about 1600 MW, the fuel elements will experience the same in-plane thermal stresses as the Phoebus-2A fuel elements

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(assuming the same coolant hole locations). For this reason, it is expected that Phoebus-1B will be run closer to 1600 MW than the 2000 MW previously considered.

Fig. 12. Power levels in Phoebus-1B to yield same in-plane thermal stress as in Phoebus-2A.

Structural Analysis of the Graphite Reflector Cylinder

The current Phoebus-1B design operation conditions will subject the graphite reflector cylinder to larger ΔP loads and higher heating rates than encountered in previous reactors. The structural analysis and evaluation of possible failure modes of the cylinder are undergoing intensive review and study.

Comparison of the predictions from analytical calculations of the stresses, strains, and deflections in the cylinder with results from laboratory static load tests have indicated excellent agreement. This gives assurance that the stress analysis of the cylinder under reactor operating loads and temperature gradients is reasonably accurate.

The predictions indicate two possible major failure modes:

- (1) Buckling of the cylinder due to the combined axial and radial compressive loads resulting from the core ΔP .
- (2) The high compressive stresses in the cylinder near the core exit end which might result in a "crushing" failure.

The first type of failure is considered improbable since static tests of a cylinder have subjected it to a radial ΔP of 315 psi (and corresponding axial load equivalent to this simulated core ΔP) without

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buckling. The current estimate of the radial ΔP for the Phoebus-1B design operating conditions, which corresponds to a power of 2000 MW, flow rate of 123 lb/sec, and fuel element exit H_2 temperature of $4600^\circ R$, is calculated to be ~ 250 psi, corresponding to a core ΔP of 170 psi.

The high compressive stresses at the core exit end of the cylinder (at and near the contact interface with the nozzle skirt) have been relieved to some degree by a redesign of the graphite transition ring from its previous configurations. This ring, which was increased in length from 1.5 to 3.5 in., takes the bearing loads between the cylinder and the nozzle skirt. Compressive stresses of ~ 3000 - 4000 psi, a result of combined ΔP loads and thermal gradients, were computed. The uni-axial compressive strength of the H⁴IM graphite is about 5000 psi. The state of stress in the cylinder is biaxial compression, however, and thus a review of the compressive (crushing) strength of the material is under way. In addition, the fracture data from the laboratory static load test which carried a cylinder to failure indicate that a margin exists.

Consequently, to the present, analyses and available H⁴IM test data indicate that the reflector cylinder is structurally adequate for the full-power run. But the margin of safety is relatively low and is based on a small number of test points. Further studies are needed to confirm this early prediction with a satisfactory degree of confidence.

The thermal stresses were computed from temperature calculations which took account of the decrease in conductivity induced by radiation damage observed in the Kiwi-B-4E reactor experiment (cf. Quarterly Report LA-3212-MS, p. 6 and LA-3308-MS, pp. 33-34). The maximum thermal stresses and strains occur near the axial midplane of the cylinder (at about 20-30 in. from the core inlet). The tensile thermal stresses on the (cooler) outer surface of the cylinder are reduced considerably, however, by the compressive stresses developed by the pressure loads.

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Additional analysis, static load tests of cylinders, and material strength determinations are in progress to verify the adequacy of the reflector cylinder for the Phoebus-1B design operation conditions.

Phoebus-1B Radiation Heating

Phoebus-1B radiation heating has been estimated with the QAD point kernel program for the pressure shell clamp band and for the region near the RN-6 nozzle flange. A γ source of 172 MW was used for this calculation, typical of a time about 6 min out on the 2000-MW hold. Energy deposition rates up to 6.5 W/g are encountered in the Al clamp band and somewhat smaller rates apply to the nozzle flange.

Phoebus-1B Shield Neutronic Interaction

Test cell shields for Phoebus reactors are of concern because of potential interaction on reactivity and power distribution. It is possible that final fission distribution will have to be measured with the shield or a mockup in position; consequently, a mockup shield is being procured for Kiva measurements on PARKA and Phoebus-1B.

A rough calculational survey of shield interaction effects has been made with the DTF one-dimensional transport code. These calculations were radial k-calculations using Kiwi-B-4E reactor specifications. The one-dimensional cylindrical calculation requires representation of the control rods as a uniform boron (B) sheath located in the Be reflector. Either the position or density of this sheath can be adjusted in order to simulate the influences of actual rods. A single experimental check point of the contribution of an external hydrogenous reflector is provided by a measurement of the effectiveness of polyethylene outside the pressure shell of a Kiwi reactor. In this measurement a 2-in. thick, 36-in. wide equatorial reflector, wrapped around the pressure vessel, was worth 1.8\$ in reactivity. Extending this reflector to the full core length (52 in.) would probably increase the reactivity contribution to a little over 2\$.

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Table 5. Reactivity and Power Perturbation by Various Shield Geometries

Shield No.	Shield Description	N_B :*	0	0.002	0.005	0.01	0.014
			Reactivity Addition, \$				
1	2 in. polyethylene, close fitting	6.8 (1.33) [†]	2.6 (1.14)	1.41 (1.08)	9.94 (1.05)	0.74 (1.04)	
2	0.5 in. Al + 4 in. H ₂ O, 2 in. Al (homogenized), close fitting	6.1 (1.29)	2.6 (1.13)			0.84 (1.04)	
3	Shield 2 with $\frac{1}{4}$ -in. "thick" B between reactor and shield	0.98 (1.03)	0.73 (1.03)			0.55 (1.02)	
4	Shield 2 with 15-in. gap between reactor and shield	4.5	1.8 (1.09)	0.94 (1.06)	0.73 (1.04)	0.59 (1.03)	
5	Shield 4 with 1 w/o B added to Al in H ₂ O-Al region	1.6 (1.06)	0.83 (1.04)			0.44 (1.02)	
6	Shield 5 with B concentration doubled	1.3 (1.05)	0.73 (1.03)			0.42 (1.00)	

* N_B = Boron concentration in units of 10^{24} atoms/cm³.

[†] Values in parenthesis give: Ratio of edge to central power with shield/Ratio of edge to central power without shield.

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Results of the computational survey are summarized in Table 5. Shield No. 1 was run in order to estimate what B sheath gave best agreement with the 2-in. polyethylene experiment. The value of 2.6\$ at a B concentration of 0.002×10^{24} atoms/cm³ is a little high but the effect of ~5 ft of shield extension beyond the core has not been included. Thus the numbers for reactivity listed in the $N_B = 0.002$ column are expected to give the most reliable prediction of experiments to come. As a result, a borated H₂O shield 15 in. from the pressure vessel is estimated to contribute less than 1\$ in reactivity and to perturb fission density by a few percent. Figure 13 shows the variation of shield reactivity contribution with control sheath B concentration.

Fig. 13. Reactivity added to Phoebus-1B by various shield configurations.

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II. PHOEBUS-2

PHOEBUS-2 REACTOR

Introduction

The Phoebus-2 experimental reactor will incorporate several basic design changes to increase the power density and power from the Phoebus-1A levels. The fuel region will be approximately 55 in. in diam (as opposed to 35 in. for Phoebus-1), but will retain the same fuel element length (52 in.). General design details were given in the preceding Quarterly Report, LA-3341-MS, p. 27.

Structural

The proposed peripheral support block, tie tube, filler, and slat arrangement for Phoebus-2 has been stabilized. A geometry has been selected that should permit the use of either gathered-flow or angled-flow support blocks.

The equations describing the dynamic behavior of the reactor structure were completed and the numerical values were derived of inertia, weight, and spring terms in the dynamic equations. Work was started on setting up the analog computer model.

Lateral support leaf springs made of 7079-T651 have been received and will be tested for their characteristics in the near future.

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Reflector System

Reflector system components are approaching final design status. The Be components still need only the final adjustment of cooling hole sizes and locations, plus a possible slight tailoring of the control drum annulus. The reflector system hardware is nearly ready for detailing.

Heat Transfer - General

Tie tube calculations were completed (using the ~~OPTIØN~~ code) for three run profiles in Phoebus-2. The core exit temperatures during the shutdown holds were 2000°R , 1500°R , and 1000°R , respectively, for the three runs. The calculations indicate that the lower temperature hold does result in lower tie tube temperatures, for a tube at the center of the core. An additional calculation was made for a periphery tie tube with a 1000°R hold. The edge tube flow rates were found to vary from 0.7 (at full power) to 1.25 (at the hold) of the rates for a center tie tube.

Tie tube calculations were made for an emergency shutdown using a high-pressure dewar as a coolant source. The results indicated that the maximum tie tube temperature reached during such a shutdown would be 1600°R ; this is an acceptable value.

Two-dimensional temperature distributions were obtained of a periphery section at Station 28. The solutions are for large filler elements both with and without coolant holes, and the results are shown in Figs. 14 and 15. The calculations are being continued for other axial stations.

Reflector Thermal Analysis

The WANL SHYP II code was received and modified for use with the LASL IBM System. A model of the ladder seal geometry was prepared and debugged. Calculations from this model will be coupled with calculations on the interface cylinder and slats.

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Fig. 14. Two-dimensional temperature distribution in periphery of Phoebus-2, with cooled filler.

Fig. 15. Two-dimensional temperature distribution in periphery of Phoebus-2, without cooled filler.

Beryllium cooling calculations are well under way using the ~~OPTION~~ code to establish the cooling requirements. Two-dimensional calculations have been started using the MAÑANA code; they will be used primarily to verify the ~~OPTION~~ calculations. The results are nearly complete enough for decisions to be made on such questions as multiple hole sizes and the relative sink strengths of annuli and holes. Transient thermal calculations have yet to be done.

Phoebus-2 Fabrication

Tie Tubes

The first four development tie tubes produced by the outside vendor have been pressure, leak, and load tested. Microphotographs of

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sections of the failed tubes indicate that the quality of the tubes is below that required. Several changes were made in processing as a result of the faults found in the first assemblies. The second batch of tubes is now in process.

Control Drums

Two Al blanks have been machined and are being chem-milled. For the outer cylinder, ACFI has developed the welding technique and is working on heat treat response.

Beryllium Reflector

Seventeen Be blocks have been recieved of the 54 ordered from General Astrometals. Three of these were rejected because of cracks, and one has not yet been inspected. Seven more blocks are being held at the plant pending acceptance of the nondestructive inspection methods and packaging used. General Astrometals radiographic techniques now appear to be satisfactory. The need for ultrasonic testing was clearly demonstrated and they are preparing to use it.

All 54 of the Brush-supplied set of blocks have been made. Six have been received and were inspected locally. One had a somewhat questionable high-density region, but the others are acceptable. The question as to whether the remaining blocks should be inspected locally is being considered.

The trepanning order was placed with Brush Beryllium. Brush will develop and prove their process on a full size block, one not yet delivered to IASL. Mechanical burning will be tried first, with Eloxing considered as a backup process.

Electric Stepping Motor Control Rod Drive

Parts for the first prototype electric stepping motor actuator for Phoebus-2 have been completed and assembled; testing is under way.

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The mechanical design is being reviewed for possible simplification from the standpoints of making the housing parts and assembling the actuator. One item under consideration which will greatly simplify the actuator is the elimination of the pneumatic lock. It is felt that securing the motor excitation leads will provide a safe method of preventing the control rods from being inadvertently rotated. Individual key locks could be provided to secure each actuator. Similar control of the clutch leads would provide an additional backup.

The electric stepper motor actuator will first be used in the Phoebus-2 Zepo. The present linear control rods will be replaced by rotary rods and an automatic control system based on rod position used to regulate power. The position resolution of the system will be about 0.01° .

Neutronic Calculations

A neutronic model was established for the current Phoebus-2 design. The reactor contains 257 kg of U distributed in six core regions. Fuel loadings vary from approximately 100 to 285 mg U/cm³.

Several average reactivity worths for core materials were calculated and are shown in Table 6. For comparison, the corresponding

<u>Table 6. Core Average Reactivity Worths</u>			
<u>Material</u>	<u>Calculated Phoebus-2, β/kg</u>	<u>Calculated Zepo, β/kg</u>	<u>Measured Zepo, β/kg</u>
U (93% U ²³⁵)	+ 9.4	+ 7.7	+ 7.7
C	+ 2.6	+ 2.65	+ 2.8
Nb	- 3.9	- 3.2	- 3.2
Ta	- 60.2		
H	+368.0		+430.0

Phoebus-2 Zepo calculations and experimental measurements are included in the table. The radial dependence of the U worth is shown in Fig. 16.

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Fig. 16. Radial dependence of U (93% U^{235}) worth in Phoebus-2.

Fig. 17. Effect of hydrogen in Phoebus-2.

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The full power H reactivity change was calculated to be + 4.88\$; of this, 4.28\$ is contributed by H in the core and 0.60\$ by H in the interface and reflector. These results are based on a uniform core H worth of + 3.68\$/kg (obtained from one-dimensional DTK calculations) used in conjunction with the predicted full power H density profile and a previously prepared axial worth curve. In a past investigation, this method yielded somewhat higher worths than did corresponding two-dimensional calculations. The effect of H on the fission distribution is shown in curve A of Fig. 17. The H increases the fission density at the core edge by 17%.

The effects of full-power temperature on reactivity and power distribution were investigated. The resulting reactivity change was calculated to be -3.86\$, of which -3.29\$ is contributed by neutronic temperature effects and 0.57\$ by core expansion. The effect of full-power temperature on the radial power distribution is shown in curve B of Fig. 17.

From the above results the overall hot-to-cold changes can be estimated. Combination of the reactivity changes contributed by H and by temperature yields a net increase of 1.02\$. The combined effect on radial power distribution is shown in curve C of Fig. 17. This curve does not include the effect of control drum motion which will eventually be measured in Phoebus-2 Zepo.

One-dimensional calculations were performed to investigate the effect of an external cylindrical shield on reactivity and radial power distribution. In these calculations the B sheath was omitted from the calculational model since it was felt that this sheath would be more effective in isolating the shield than would the actual drum configuration. Using a three-region shield model, it was found that the shield contributed +75¢ to reactivity and increased the edge power by 5%. Whereas the presence of control drums should reduce the reactivity effect, the power distribution effect might persist in areas between drums. Since the

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shield is considerably longer than the reactor, axial reflection at the exit end might produce a significant perturbation, especially on the axial power pattern. This effect requires a two-dimensional analysis.

Reactivity Worth of Graphite, Uranium, Niobium and Hydrogen

The effectiveness of graphite, U, and Nb has been measured along the axis of the Phoebus-2 Zepo core (without support blocks). The results are given in Figs. 18, 19, and 20. The U and Nb samples were foils of metal rolled up to form slugs and were moved within holes in the Zepo elements. Because of some self-shielding in these samples, the average values in Figs. 19 and 20 are normalized to unity. Graphite samples were larger and longer solid cylinders inserted in spaces vacated by removing support elements. The point marked A in Fig. 18 is from an earlier measurement in which 1-in. long pieces of support element were added to the top of the core. For the point marked B, all the support elements were raised 1 in. Both points are corrected to an axial location. The disagreement with Honeycomb results (Fig. 18) may be due to streaming in the larger Honeycomb channels. The axial averages from these graphite profiles agree well in both cases with the values obtained by direct measurement with full-length elements. It should be pointed out that the average worth for graphite given in Fig. 18 is for material placed down the very center of the core; axial curves at other radii (particularly near the core periphery) would give lower average worths.

Figure 21 shows the reactivity worth of H as a function of radius in the core compared with earlier results from Honeycomb. The ordinates give axially-averaged values for uniform axial density. The measurements were made by using polyethylene strings and correcting for C.

The resulting core average worth for uniform H₂ density is 4.3\$/kg.

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Fig. 18. Axial dependence of graphite reactivity worth in Phoebus-2 Zepo compared with that in Honeycomb.

Fig. 19. Relative axial variation of U reactivity worth in Phoebus-2 Zepo.

Fig. 20. Relative axial variation of Nb poisoning in Phoebus-2 Zepo.

Fig. 21. Radial variation of H reactivity worth in Phoebus-2 Zepo and Honeycomb cores.

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Fig. 22. Reactivity increase accompanying Phoebus-2 Zepo core compression.

Zepo Core Compression vs Reactivity

Reactivity changes associated with radial motion of the Phoebus-2 Zepo core outer surface were measured for six positions relative to the Al reflector cylinder. Starting with fuel elements initially quite loose, the core was compressed in steps by adjusting screws through the Al cylinder. The curve in Fig. 22 indicates that the core is not compressed uniformly throughout the range of measurement. The value of the asymptotic radial coefficient appears to be close to 1.3\$ /in.

Effectiveness of Production B₄C-Cu Control Plates

The degree of poisoning by a nominal 40 v/o sample plate of B₄C-Cu composition formed with granular B₄C was compared with that of earlier samples which contained finely-powdered B₄C. A boron plate enriched in B¹⁰ (of the same area and in the same location in the Zepo reflector) was used as a standard. The effectiveness of this sample was $99.0 \pm 0.8\%$ of that predicted at the same B¹⁰ atoms/cm² density from results of measurement with the earlier samples.

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Phoebus-2 Zepo Revisions

The Phoebus-2 Zepo core and interface regions have been modified to bring the system into line with current reactor design (LA-3341-MS, p. 27). The change from a 12-sided core periphery to a circular cross section gave a 1.19\$ reactivity change which compares well with the predicted value of 1.06\$.

The next major revision will be to replace a 90° sector of Zepo with a more refined and realistic version. To this end, both previous experimental results and calculations have been used to specify the U loadings of fuel elements to go into this 90° sector. Measurements will then be used to refine further the loading specifications. The reactivity analysis used to arrive at a total U inventory is summarized in Table 7.

Table 7. Reactivity Changes Involved in Converting
the Zepo Mockup to the Phoebus-2 System

<u>Reactor Differences</u>	<u>Reactivity Change, \$</u>
Control system	+ 0.3
Ta shimming	- 3.0
Core C content	+ 4.5
Nb self shielding	- 1.2
End tips and support blocks	+ 2.4
Be reflector	+ 0.1
Multizone vs three-zone loading	- 0.8
Interface region	+ 0.8
Inlet end features	0
Support tubes (Inconel)	- 1.0
Core compression	+ 0.1
	+ 2.2

It was assumed that the Phoebus-2 design point at cold critical will be with the control rods capable of increasing reactivity by 2.5\$ (4.5\$ shutdown reactivity) and with 3\$ worth of Ta shim elements in the core.

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The result given in Table 7 is that Phoebus-2 is expected to be about 2.2\$ more reactive than the present Zepo, and so the U inventory of Phoebus-2 will be less than the 294 kg now in Zepo. Using the value of 7¢/kg U, the predicted U inventory of Phoebus-2 is 263 kg. The new 90° sector in Zepo will be loaded correspondingly.

The radial loading variations in the 90° sector have been obtained from calculations. In estimating the loadings needed, no consideration has been given the effects of temperature, control rod position, or H on the fission distribution since all these effects depend on design details and operating conditions not yet precisely determined.

Preliminary Structural Analysis of the Phoebus-2 Interface Cylinder

A preliminary structural analysis of the Phoebus-2 stacked Al ring interface cylinder was completed (see Quarterly Report LA-3341-MS, p. 31, for a brief description of the design). The stress analysis considered the preliminary design values of radial and axial ΔP loads. The junctions between the rings were assumed to carry no moments but maintained radial deflection continuity (hinged joints). The results of the calculations indicated that only nominal stress levels exist in the cylinder ($\sigma \lesssim 20,000$ psi) for the major portion of its length. High stresses in the area of the core support plate attachment to the cylinder were reduced to acceptable levels by a redesign of the cylinder in this region. The radial deflection (contraction) of the cylinder was shown to be mostly due to the temperature.

The structural analysis of the interface cylinder will continue as the load and temperature data are refined and the configuration evolves.

Phoebus-2 Fuel Element Bending Stresses

The fuel elements, graphite filler strips, and slats at the Phoebus-2 core periphery will be subjected to bending stresses when the

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radial bundling pressure forces them to conform to the core radial thermal expansion. A detailed analysis of these bending stresses has been completed.

The stress was calculated by assuming that the fuel elements (and filler strips and slats) can be considered as simple beams according to the relation

$$\sigma = RC \frac{d^2}{dz^2} \left[(\alpha \Delta T) \right] E,$$

where R = radius to neutral axis of element, C = distance from neutral axis to point where stress is to be evaluated in the element, E(T) = modulus of elasticity, $\alpha(T)$ = transverse coefficient of thermal expansion, $\Delta T(z)$ = change in temperature of element from ambient to reactor operating temperature, and z = axial distance from core inlet. The elements were considered to have zero bending stresses at their ends and inter-element friction was neglected. Typical results for the bending stress for three typical components at the core periphery are indicated in Fig. 23. The nominal variation of the input quantity $(\alpha \Delta T)$ is given in Fig. 24 for Phoebus-2 design operating conditions. The analysis also evaluated the radial bundling pressure required to maintain a compacted core, since the fourth derivative, $d^4(\alpha \Delta T)/dz^4$, is proportional to this loading. The magnitude and detailed axial variation of the derived bundling load are very sensitive to small variations in the $\alpha \Delta T$ value.

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Fig. 23. Calculated binding stresses for Phoebebus-2 peripheral core components.

Fig. 24. Axial variation of $\alpha\Delta T$ in Phoebebus-2 components at design conditions.

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III. NRDS ACTIVITIES

THE PHOEBUS-1A TEST SERIES

Experimental Plans

The following E.P.'s were performed (cf. Quarterly Status Report LA-3341-MS, p. 56):

E.P. I - May 27, 1965. The objectives were to operate all necessary facility systems, to verify the full-power run flow profiles and programs, and to test all emergency systems. Pressure measurements made at 70 lb/sec flow yielded the following ΔP 's in the LH₂ pipeline: 2.6 psi across 150 ft of line with 11 elbows; 10 psi across ACV-16; and 53 psi across plug and car piping. The small drop across the long line agreed with predictions but the large drop near the car was not expected. It is inferred that propagation and reflection of pressure disturbances in the pipeline should occur with less damping than has been incorporated in computer models. Consequently, the measured pipeline pressure-to-pressure transfer function is expected to differ from that which has been calculated. Laboratory experiments are being planned to clarify some of the phenomena involved.

E.P. II - June 10, 1965. The objectives were: (1) to make control rod frequency response measurements and scram time measurements while reactor was subcritical; (2) to obtain initial criticality of the Phoebus-1A reactor; (3) to irradiate U²³⁵ and Au wires at low power for

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analysis and calibration of the Test Cell Neutronic System; (4) to make dynamic response measurements on the log power control loop; and (5) to perform automatic reactor startups.

E.P. III - June 23, 1965. The objectives were: (1) to run the full-power programs with the detectors in the low-power position; (2) to set the neutronic detector stops to agree with wire analysis from E.P. II; (3) to operate all systems necessary for the full-power run in order to check system performance and/or systems interaction; and (4) to provide a final dress rehearsal of the full-power run.

E.P. IV (Full Power Run) - June 25, 1965. The objectives were: (1) to operate the Phoebus-1A reactor at design power, temperature, and LH_2 flow rate in order to obtain information regarding fuel element and core design; (2) to obtain data for use in programming rod position on the planned restart, where log power will not be program controlled; and (3) to make frequency response measurements of the power and temperature loops and pressure to pressure measurements during the full-power hold. The observations made during the course of E.P. IV are described on p.51, et seq.

Flow Shutdown and Scram Chain Inputs

The shutdown and scram chains were modified prior to Phoebus-1A in order to implement changes in philosophy regarding procedures following an emergency LH_2 shutdown or scram. In addition, both speed channels were used as inputs to the flow shutdown chain. Filters on the inputs were retained from the Kiwi-B-4E-301 test in order to reduce the possibility of an inadvertent shutdown due to a signal transient. These inputs and their filter time constants were as follows:

Rod hydraulic pressure	1 sec
Servo hydraulic pressure	1 sec
Overspeed	5 msec
Turbine inlet pressure	5 msec
Fixed power	5 msec
Period	Less than 1 e-folding time.

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The scram chain and flow shutdown chain inputs, trip levels, and outputs were as follows:

<u>Inputs</u>	<u>Scram Chain</u>	
	<u>Value</u>	<u>Remarks</u>
1. Fixed Power	2200 MW	
2. Floating Power	2 x demanded power	Auto-bypassed at 150 MW
3. Period	0.1 sec	Auto-bypassed at 150 MW
4. Rod Hydraulic	400 psi (low)	A pressure in each of the two manifolds is monitored; either of these can produce a scram.
5. Chief Test Operator (CTO) Button		
6. Flow Shutdown		

Outputs

1. All rods commanded in at 400°/sec.
2. Pneumatic locking pins inserted.
3. LH₂ flow rate decreases exponentially to 20 lb/sec with a time constant of 3 sec if in program flow rate control.

Switching to GH₂ coolant will be performed by the CTO from a contingency checklist.

Flow Shutdown Chain

<u>Inputs</u>	<u>Value</u>	<u>Remarks</u>
1. Turbo-pump speed	34,000 rpm	Two speed channels are monitored either of which can produce a flow shutdown.
2. Turbine inlet pressure	700 psi	
3. Servo valve hydraulic pressure	1600 psi (low)	

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Outputs

1. Turbine valve (ACV-3) closes.
2. LH₂ bypass valve (ACV-2) opens.
3. ACV-16 closes.
4. PCV-89 switched from Position to Flow (Pressure) control.

Pressure demand of PCV-89 is programmed to $0.6 P_d$ with a transcendental rise to $1.2 P_d$ pressure at 5 sec, where P_d is the pump discharge pressure (see p. 8).

Studies showed the desirability of instituting new methods of emergency shutdowns which would (1) cause less severe rates of change of temperature with time within the reactor core, and (2) provide more efficient usage of the coolant fluids. These studies were used in developing the following emergency shutdown cooling approach for the Phoebus-1A full-power run.

1. Different actions should be taken when LH₂ cooling is available and when it is not. In particular, the scram and flow shutdown scrams should not be tied together as they were for the Kiwi-B-4E-301 test.
2. If possible, LH₂ flow should be maintained with the turbopump.
3. If pumping capability is lost, high-pressure GH₂ should be used to push the LH₂ stored in the propellant line through the reactor at a rate which will produce an acceptable $\Delta T/\Delta t$, followed by gas cooling at essentially the maximum available rate.

In order to implement the above, the following modifications were made in the Control Room circuitry.

1. In the event a scram is initiated, the programmed LH₂ flow rate demand is switched to a signal which decays exponentially with a time constant of 3 sec until the flow rate reaches 20 lb/sec. From this point, action is taken by the CTO as necessary to complete the LH₂ system shutdown and switch to GH₂ cooling of the reactor. Analog computer studies indicated that a time constant equal to 1 sec was most desirable; however, past

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facility runs had shown that a value of less than 3 sec will cause the pump to be driven into stall. Additional studies indicated that an LH₂ flow rate decay with a time constant of 3 sec would produce acceptable $\Delta T/\Delta t$ within the reactor core.

2. Flow shutdown chain activation will, in addition to scrambling the reactor and shutting down the LH₂ pumping system, switch PCV-89 (GH₂ flow control valve) to Flow (Pressure) control, which allows the LH₂ pressure to decay to 60% of the value at the time the shutdown occurs, then increases the pressure to 120% in 5 sec. This action will allow the LH₂ stored in the piping to be discharged through the reactor in ~ 2.5 sec. GH₂ pressure can then be increased by the CTO to supply the necessary cooling.

Control Systems

With the exception of the temperature controller, the control systems and various controllers used during the Phoebus-1A test series were identical with those in the Kiwi-B-4D-202 and -4E-301 reactor tests. The temperature controller for the Phoebus-1A test was changed to

$$G(s) = \frac{0.14 \left(\frac{s}{0.2} + 1 \right)}{s \left(\frac{s}{10} + 1 \right)} .$$

There were still the clamps of +15% and -50% on the output of the temperature controller.

Chronology of Phoebus-1A Full-Power Run (E.P. IV)

Pre-Run

A problem that caused considerable concern prior to run day was noise associated with the reactor instrumentation channels; it first appeared approximately 7 days prior to the full-power run. Efforts to

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find the cause were hampered by the fact that the reactor was inaccessible due to radiation levels still present from E.P. II. The source was found to be centered around the reactor strain gauges and so the latter were disconnected the night before E.P. IV to prevent any possible interference with necessary reactor temperature pressure and control channels during the full-power run. No other major problems were encountered and on the morning of June 25, 1965, all systems were ready.

Run Day

The only problem of any consequence during the pre-run phases on run day was an erroneous power integrator reading, which was corrected by replacing an operational amplifier in the data buffer; this in no way affected the reactor controls or feedback channels. Weather conditions caused a $2\frac{1}{2}$ -h hold after the pre-run phases of the checklist were completed, and the full-power run phase was started at approximately 1 p.m.

During the full-power run, trouble was encountered with the incoming a.c. power, LH₂ dewar level measurements, linear power indication, the core exit temperature computation, and some facility and reactor channels. The following is the sequence in which these events occurred.

About 13 sec after the CTO activated the programmers, there was a loss of the a.c. power to the Jackass Flats substation due to lightning activity between NRDS and Las Vegas. Soon afterwards the linear power No. 2 channel was lost for a period of about 100 sec. The channel indicating total LH₂ flow rate momentarily dropped to zero three times during this same period. These problems did not prevent successful completion of the startup phase to the planned hold at 60 lb/sec of LH₂. The pre-run computations were in such good agreement with the measured parameters at this point that no temperature correction was needed.

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The CTO then initiated the programmers to proceed with the full-power hold position. On the ramp a fire was reported on the test car, in the vicinity of the "belly band" around the pressure vessel. A short period was taken to assess the seriousness of the fire. Since it did not get worse, nor appear to endanger the reactor or critical test-car systems, frequency response measurements were made of the temperature loop. Next, random pulses were introduced into the RPM and FLOW loops for 1 min to obtain pressure-to-pressure transfer data throughout the facility and, hopefully, for the reactor as well.

Upon completion of this phase, random pulses of a lower frequency were introduced into the temperature loop. This was intended to give the transfer function of log power to temperature at various stations in the reactor core. The pulses in the temperature loop were continued for 4 min. By this time the reactor had been at full power for almost 400 sec and all planned experiments had been completed. A water deluge alarm was reported at about 500 sec. After 559 sec at full power, JEV-1, the main cryogenic valve of Dewar A, was commanded closed. A "zero" level alarm on Dewar B was reported at 609 sec, although the capacitance gauge indicated, incorrectly, a content of 27% LH₂; there were several high pump inlet temperatures reported at about this time. At 629 sec the ramp down (RUN) was ordered and a few seconds later the LH₂ supply was exhausted. The loss of coolant, combined with a delayed residual GH₂ bank pressure, resulted in damage to the reactor due to overheating and to the pump system.

The transients in several critical parameters associated with the loss of LH₂ at the turbopump inlet are shown in Fig. 25. Apparently at least one of the speed pickups failed due to the severe vibration of the pump, and it is doubtful if the M-501 trace represents actual shaft speed variation with time. The indicated speed excursion, which initiated the flow shutdown about 3 sec after the start of the transient, was probably fortuitous. Also during the transient the temperature controller dropped reactor power to about 500 MW.

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Fig. 25. Transients associated with loss of LH_2 at turbopump inlet in Phoebus-1A.

The flow shutdown scrambled the reactor. The gas-flow program operated properly but yielded too little flow because it was slaved to pump discharge pressure, which decayed by a factor of three during the inadvertent 3 sec of shutdown delay. Loss of core material was observed as gas flow reached the reactor. The H_2 bottles had been depleted during the run so that 11 lb/sec was the maximum flow rate attainable when the CTO increased the demand manually. The tie rod temperatures exceeded full scale and many core temperature channels were lost. The CTO attempted to get more coolant to the reactor by introducing He in addition to the GH_2 . There was a hydrogen alarm in the Pump Room, and

the television cameras located a severe leak around the turbopump. The remaining GH_2 was soon depleted, and further cooling had to be done with GN_2 . The final cooldown phase was complicated by a hole through the core, which allowed most of the gas to bypass the coolant passages. Since cooling by gas flow was quite ineffective, the reactor was allowed to stabilize at a higher temperature.

Post-Run

An entry to the test cell was made to reestablish air conditioning for the electronic equipment. This was necessary to insure control of and to retain information pertinent to the cooldown. Unfortunately, there was another power outage, causing the air conditioning to be lost again, but not before the temperature in the

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electronics room had been returned to normal. Since steady operation of the electronic equipment could not be tolerated for more than a few hours, power to the test cell was shut off. When the power was turned on the next morning, it was found that most channels suffered very little, if any, offset during this cycling process. The entire facility, both test cell and control room, was shut down electrically the morning of June 26; it remained this way until the morning of June 29, when the power was again turned on. On the afternoon of June 29, the systems were returned to test cell control by a small reentry party. Access to the test cell was severely limited due to the radiation hazard.

Behavior of Facility Systems

The new system for establishing GH_2 flow immediately upon shutdown performed as planned. Unfortunately, two situations mentioned in the chronology served to negate any benefit from this new circuitry. The speed pickups failed so that a shutdown did not occur until 3 sec after the start of the overspeed transient. During this time the reactor dropped from 960 to 480 MW and the pump discharge pressure, which the GH_2 demand was following, decayed from approximately 900 to 300 psi. The PCV-89 GH_2 system had been programmed to supply GH_2 at $0.6 P_d$, i.e., ~ 180 psig, which the system did, and the desired exponential increase to $1.2 P_d$ was achieved. Due to the low pump discharge pressure, this did not provide enough coolant and the demand was increased manually.

Even though the GH_2 demand was increased, sufficient coolant could not be forced through the core due to a lower GH_2 bottle bank pressure than had been anticipated. Subsequent investigation has shown that the turbopump, installed prior to the Phoebus-1A test series, was approximately 10% less efficient than any previous turbopump operated at NRDS. The actual GH_2 usage, together with the entire gas and fluid usage, will be discussed in more detail below, as will the dewar instrumentation which resulted in the depletion of the LH_2 supply.

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Dewar Level History and Behavior

The erroneous capacitance-type level gauge in Dewar B during the Phoebus-1A full-power run had serious consequences, as stated on p.53. The failure of the gauges has been attributed to the action of radiation, possibly a shunt effect between the electrodes caused by ionized hydrogen. Since the E.P. IV run, extensive comparisons have been made of the dewar level data between the Kiwi-B-4D-202, Kiwi-B-4E-301, and Phoebus-1A full-power runs. The most interesting observation is that the Dewar B level apparently stopped decreasing at the 73-74% mark, as indicated by the capacitance gauge, during all the reactor runs for the following time intervals:

Kiwi-B-4D-202	63 sec
Kiwi-B-4E-301	58 sec
Kiwi-B-4E-301 (restart)	24 sec
Phoebus-1A	130 sec.

During these periods the only indicated dewar flow, defined as the LH_2 flow obtained by differentiating the dewar level signals, was from Dewar A. Furthermore, it was considerably less than the total LH_2 flow rate measured by a venturi (F-23). At the end of these intervals the Dewar B level started to drop again. For a time during both the Kiwi-B-4D-202 and -4E-301 reactor runs, the total dewar flow exceeded the F-23 flow. The flows finally equalized and remained that way until the end of the run. The integrated dewar flow agreed with the integrated F-23 flow within 1% for the Kiwi-B-4D-202 and -4E-301 runs. In addition, the dewar levels read correctly at the end of both runs. During the Phoebus-1A run, however, the total dewar flow after the Dewar B plateau period was $68\frac{1}{2}$ lb/sec, compared with an F-23 flow rate of 71 lb/sec. Total integrated dewar flow for the full-power hold was 34,700 lb, as compared with an integrated F-23 flow rate of 42,600 lb. An interesting observation is that the indicated dewar flow following the Dewar B leveling on the Kiwi-B-4D-202 and -4E-301 runs cancelled the effect of decreased dewar flow

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during the level period. This behavior had been noted prior to Phoebus-1A but was not studied in detail; it was attributed to flow characteristics of the tee where the two dewar outlet ducts join to form the main propellant line. In retrospect, the correlation of this effect with hot runs should have been a clue to potential trouble.

The cancelling phenomenon did not occur on the Phoebus-1A run. Dewar B was indicating 27% LH₂ level at the time of loss of LH₂ flow, and the Dewar A level indication returned to 6% after the shutdown. Data from the Facility Checkout (EP-1) and the Heat Exchanger Series were investigated. No leveling of the Dewar B level was apparent and the integrated dewar flow agreed with integrated F-23 flow. Of course, no high radiation fields were present during these runs.

Experience has shown that dewar weights are not a reliable indication of LH₂ flow. In some cases the weight change agrees quite closely with the total flow. In other instances, the dewar weight changes in a stepwise manner and does not agree with dewar level changes or F-23 flow, presumably due to effects of wind, pipe line stresses, and temperature.

Work is at present under way to evaluate a "fathometer" level indicator to replace the capacitance gauges. The former operates by the reflection of an electromagnetic signal and is expected not to be affected by radiation.

Comparison of Pre-Run Estimates with Actual Fluid Usage

The actual fluid use during EP-IV is compared with pre-run predictions in Table 8. The difference between the predicted and actual GH₂ usage can be accounted for by the decrease in pump efficiency in the unit installed prior to the Phoebus-1A test series. This turbopump exhibited some operating characteristics during E.P. I and E.P. IV not noticed on previous pumps. Past experience has been that measured values

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Table 8. Phoebus-1A Gas and Fluid Usage in E.P. IV

	<u>Initial Inventory</u>		<u>Pre-Run Phase</u>		<u>Run Phase</u>		<u>Ramp Down & Cool Down</u>	
	<u>Predicted</u>	<u>Actual</u>	<u>Predicted</u>	<u>Actual</u>	<u>Predicted</u>	<u>Actual</u>	<u>Predicted</u>	<u>Actual</u>
LH ₂ (lb) 59,000 (t)	63,000 (t)		5,000	6,100	45,300	51,550	2,700	0
GH ₂ (lb)	8,400	8,400	500	700	4,000	5,500	3,920	2,200
GN ₂ (lb)	117,000	126,600	33,000 (including Run Phase)	24,800		9,500	91,000*	47,900
He (lb)	10,600	10,600	0		0		0	2,100

(t) Includes 3000 lb in each dewar which is below the "zero" level gauge and alarm.

* LN₂ pumper standing by for additional requirements

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of speed, pressure, and flow rate have agreed, within instrumentation limits, with the pump map. For the Heat Exchanger runs, for example, the agreement was within 2%. The measured and pump map values disagreed by as much as 10%, however, on the Phoebus-1A runs.

Shutdown and Post-Cooling Fluid Utilization

Flow Shutdown

At 23195 sec, i.e., 5 sec after the ramp down had been initiated, a speed channel (M-501) for the NFS-2 pump stepped to approximately 41,000 rpm and initiated a flow shutdown. The reactor power was approximately 50% of design at this point. The shutdown initiated a reactor scram and switch to the GH_2 pressure loop (PCV-89). This loop demanded 180 psig at P-89 (see p. 55), and shortly thereafter this was increased manually to 560 psig. At 23204 sec, PCV-89 stem was 100% open and GH_2 flow demand could no longer be supplied. At 23224 sec, He was introduced but adequate cooling could not be maintained and GH_2 flow was continued. At 23415 sec, GH_2 flow was stopped and GN_2 flow introduced, but again core temperatures could not be decreased and GH_2 flow was reestablished until the GH_2 bottles were depleted at 24367 sec.

The calculated GH_2 flow rate for 560 psi at P-89 is 11.05 lb/sec. Calculations indicate the maximum expected ΔP across PCV-89 at the full open position and the above flow rate to be 149 psid. The observed pressure drop was 210 psid at the corresponding time interval. Pre-run calculations predicted that a pressure of 1080 psi at P-89 (upstream of venturi) would be required to flow 21.5 lb/sec to cool the reactor adequately following an emergency shutdown. The tank farm pressure required to achieve this pressure at P-89 was calculated from the observed ΔP to be 1680 psi. The increased pressure drop across PCV-89 has not been previously observed as flow conditions have not required that this valve operate at the full open position. Calculations of the ΔP across the valve in the 5 to 10% region were in good agreement with observed data.

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Post Cooling

Reactor cooling with GN_2 was reestablished at 24367 sec. Prior to this point it was realized that core temperatures could not be maintained below 1400°R and the GN_2 was used to cool the reflector and core support plate. At 50400 sec the reflector and core support plate were cooled to near ambient with He. A 5 lb/min GN_2 flow was then established. At 55800 sec the cooldown monitoring operation was concluded.

Utility and Critical Power Systems

Since power failures were a major distraction during the Phoebus-1A E.P. IV run and caused difficulty during the post-run period, the following system description is presented as background information.

The electrical power system at NRDS is designed to provide continuous service in the event one source of power should fail. During facility operation two primary sources of a.c. power are available. These are (1) the normal commercial power supplied by Nevada Power, and (2) a 600-kW diesel generator unit at the Control Point (C.P.). Battery banks of 28 V, located at the C.P. and test cell, back up certain systems, primarily 28-V control and indication power. Emergency lighting in the Control Room is supplied by a 125-V battery bank located at the C.P. substation.

Commercial power is supplied to the NRDS via a 138-kV transmission line from Las Vegas. The 138-kV incoming line enters Jackass Flats substation and is reduced to 69-kV for transmission to all facility substations at NRDS. Within the Jackass Flats substation, the 69-kV line is stepped down to 12.5 kV for an additional transmission line to the critical bus at the C.P. substation. From the C.P. substation the 12.5-kV line passes through a paralleling breaker (incoming line B) to the critical power bus. During nontest periods this line normally supplies power to the C.P. Building. The 69-kV power system supplies both the C.P. and test cell noncritical power loads through their respective substations.

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The 600-kW self-contained diesel generating unit at the C.P. is placed on line only during test periods by paralleling the 12.5-kV generator output with the incoming 12.5-kV line B. Power at 12.5 kV is transmitted to the test cell substation where it is reduced to 4160 V, then to 208/120 V at the C.P. for test cell use. Both the C.P. and test cell feeder lines are equipped with overcurrent protected breakers. Distributed power at the C.P. and test cell is series fused through system branching.

A portion of the 120-V a.c. critical power is reduced and rectified to 28 V d.c. at the control point and test cell. This system is used to power binary commands and indications. A 28-V battery bank is floating on line with the above system and will supply necessary power in the event a failure of the critical power bus occurs. The 28-V power system is used primarily to command and indicate positions of the ON-OFF block valves (OBV's) located at the test cell. Most OBV's require 110-V a.c., and loss of critical power will prevent further repositioning.

The critical power system is placed in operation 2 days prior to each E.P. This continues until the test is complete and the test cell has been secured. The critical power system is brought to operating conditions via a checklist in which the test cell critical bus is switched from utility power feeder to the critical power feeder. The diesel generator is then started; the generator output is synchronized with commercial power and the main generator breaker closed. The diesel generator is then loaded and maintained within 50 kW of the critical load. In this configuration, the diesel generator normally supplies most of the critical power load, and commercial power serves as a backup floating on line.

During the Phoebus-1A E.P. IV, the Jackass Flats substation breaker opened; the automatic reclosure circuit operated and commercial power was immediately restored to the C.P. substation. There the incoming B line breaker opened as expected. The diesel generator was synchronized to the commercial power, and the incoming line B breaker was manually

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reclosed some 60 sec following the outage. A very small transient was apparent on several data channels, but no further effects were noted except for the behavior of linear power No. 2 mentioned on p. 52. It should be noted that during the Phoebus-1A full-power run, the test cell air conditioning was lost on the opening of the test cell motor control center breaker which supplies this system. The breaker was not equipped to reclose automatically due to prior experience with a burned out compressor motor during power failure. Furthermore, it had not been placed on the critical power bus, because the test cell systems requiring cooling are operable for approximately several hours following loss of cooling.

NFS-2 Turbopump System

As already indicated, the NFS-2 turbo-machinery suffered damage during the shutdown phase of EP-IV. Upon inspection, the speed coupling was found to be still in place and apparently undamaged. However, when the lock ring on the turbine side of the coupling was removed, all but two of the 20 balls fell out because most of the inboard spring clips holding the balls to the turbine shaft had been broken off. The balls themselves appeared undamaged.

On decoupling, the turbine turned freely, although there was a quantity of lube-oil in the area of the inboard bearing indicating perhaps that vibration had damaged the seal. The pump was not frozen and could still be turned by prying on the shaft gear teeth with a screw driver. Other than some evidence of graphite seal wear on the pump outboard shaft, no other external damage to the pump and turbine was evident. The speed collar was still firmly bolted down and although the two electromagnetic speed pickups had been ground down (about 0.020 in.) by the gear teeth at the time of the pump unloading and subsequent high vibration, the sensing coil on one of the two pickups showed electrical continuity and the other did not.

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The NFS-2 pump and turbine damaged during the Phoebus-1A test, were shipped to Rocketdyne for disassembly and inspection. Rocketdyne has been directed to photograph all damaged components and submit the photos and a report to LASL.

Systems Behavior

Data Systems

The data system performed very well indeed with no data loss being attributable to equipment failure. Of special interest was the operation of the high accuracy "gold-plated" channel measuring core exit pressure. The result of this measurement agreed with the average of two normal strain gauge pressure transducer measurements of core exit at different θ locations to 2 psi in 1000 psi.

The new carrier system was put into operation for the first time with not very satisfactory results. Drift and noise were experienced on the four channels using this equipment. In addition to the normal output, an experiment required an a.c. circuit coupled to a high-gain amplifier to permit analysis of the small ($\pm 1\%$) variation of pressure on top of the static pressure. This output was affected by the noise mentioned previously.

A reentry team on run day found three Video Instrument amplifier bin mating problems. This is a continuing difficulty, the solution for which will come with installation of the new Neff amplifiers (p. 84).

Early in run week, during an investigation of noise spikes on data and control channels, a test was run to duplicate a possible failure mode for strain gauges. It was assumed that a strain gauge in the reactor or on the test car piping somehow was shorted to ground, in particular, that the positive side of the excitation was so shorted. This is a test that is done after all instrumentation is complete before every reactor test. It was found that, upon striking ground, a pulse was somehow induced into thermocouple channels, control channels, and pressure channels of an

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amplitude that could cause a shutdown. After 3 days, during which the cause of the problem could not be located, the strain gauge measurements on the leaf springs, the rods, nozzle, and cart piping were cancelled (total 22 channels). As a result of this test, the grounding system is being examined in detail and extensive redesign is anticipated.

Neutronics System

The calibration run phase of Phoebus-1A, E.P. II put a total of 22.8 MW-sec on the reactor as measured with U wires. The Au wire data were in agreement with this result. The facility detector system was in the same position as for Kiwi-B-4E-301. The power integral obtained for the run was 20 MW-sec, as measured by these external neutron detectors.

Two additional detectors, one a γ chamber and the other an uncompensated B-lined ion chamber, were calibrated on the PARKA reactor. These averaged 18.25 MW-sec for the calibration run. Since there was no Kiva wire irradiation for Phoebus-1A and since the PARKA reactor contained mainly oxide elements, the front ram No. 1 position was left unchanged from the Kiwi-B-4E-301 test, and the remaining ram positions adjusted to obtain the correct current ratios.

Rabbit integrals were, therefore, expected to be 12% higher than the neutron detector integrals. This was found to be the case on the scaled down full-power run (E.P. III), where the rabbit integral came out 13% higher than the neutron detector integrals.

The Au wires irradiated on E.P. II were analyzed at NRDS and an IBM 704 printout with computation of the reactor power was delivered to the control room less than 30 min after removal of the wires from the core. The speed of analysis of Au wires suggests the possibility that the calibration run scaled down full-power runs could be compressed into the

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same E.P. if schedule requirements warranted it. Gold wires have yielded power determinations nearly identical to U wires on three reactors, as indicated below:

<u>Reactor</u>	<u>Uranium</u>	<u>Gold</u>	<u>Difference</u>
Phoebus-1A	22.8 kW	23.4 kW	2.6%
NRX-A3	(11.0 kW)*	10.4 kW	(4.8%)*
NRX-A2	6.55 kW	6.48 kW	1.0%

*The precision of this number is impaired because the U wires were not cut to correct length before solution for radiochemistry. A power of 10.6 kW was assumed for the calibration run by NTO.

One of the external detectors (Linear No. 2) was reading 70% higher during the calibration run than any of the other detectors in the Neutronics System. This was a new RSN 15A compensated B-lined chamber which replaced a detector of the same type that was not compensated properly. Because of the increased sensitivity of this detector, it was removed after the calibration run and checked. It was found that the new detector was 1.71 times more sensitive than the RSN 15A detectors which had been in the system for some time. Since the wide variation in sensitivity was undesirable, an old detector was placed in the Ram No. 2 canister. The scaled down full-power run showed the sensitivity of the two linears to be equal to within a few percent.

The commercial power failure at the start of the ramp to full power put a transient on the power lines causing linear power No. 2 to go into saturation in the negative direction. This condition was held for 55 sec after which time it resumed reading normally. This was the only neutronic channel affected by the power transient (p. 62).

On the intermediate and full-power holds there was zero temperature correction, indicating fairly close agreement between thermal and controlling neutronic power.

The log channels were expected to average 12% higher at design power than the linear channels. This is due to the log diode error at

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design power. A voltage correction was applied to the power programmer prior to the run to remove this error. The actual spread in the log readings were greater than this with Channel No. 2 reading 15% higher than expected.

The thermal power at various times during E.P. IV are compared in Table 9 with results of other measurements. An attempt to determine

Table 9. Comparison of Thermal and Other Power Measurements

<u>Time</u>	<u>Thermal Power, MW</u>	<u>Selected Linear, MW</u>	<u>Reference Neut. Det.,MW</u>	<u>Reference Gamma Det.,MW</u>
22510	610	573	521	608
22600	1090	1055	964	1141
23000	1070	1005	915	1122
23180	1050	955	898	1117
	Log No. 1	Log No. 2	Log No. 3	Log No. 4
22400	627	720	600	600
22600	1255	1440	1070	1020

the axial-to-radial fast neutron leakage ratio as a function of power level was unsuccessful due to insufficient activity on the radial detector during E.P. II. However, an average reactor power level of 1095 MW was obtained from the axial $(\text{NH}_4)_2\text{SO}_4$ rabbit during the control room time interval from 22623.5. This agrees well with thermal measurement of 1090 MW for the time 22600 sec.

The power integrals for E.P. II, E.P. III, and E.P. IV for the Phoebus 1A series are summarized in Table 10 on p. 67.

Fission Product Losses During E.P. IV

The fractional losses of 21 fission-product chains and of U to the gas stream during the full-power test of the Phoebus-1A reactor have been computed from analyses of air samples collected by two RB 57C

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Table 10. Phoebus-1A Power Integrals (External Neutron Detectors)

E.P. II	Wire irradiation phase	20.0 MW-sec
	High power ram check phase	17.6 "
	High power automatic start and rod worth measurement	3.86 "
	Total	41.5 "
E.P. III	Ram adjustment phase (approximate)	78 MW-sec
	Scaled down power run	560 "
	Total	638 "
E.P. IV	Full Power Run	7.11×10^5 MW-sec

aircraft. The results are given in Table 11, based on an assumed loss of 50% for Cd^{115} . Losses which occurred during the accident and post-run cooldown are not included. It is estimated that about 1% of the gross fission-product inventory was released to the atmosphere.

Table 11. Loss of Fission-Product Chains from Phoebus-1A

<u>Isotope Measured</u>	<u>Percent of Chain Lost</u>	<u>Isotope Measured</u>	<u>Percent of Chain Lost</u>
Sr^{89}	3.5	Te^{132}	1.9
Y^{91}	3.8	I^{133}	1.7
Y^{93}	2.6	I^{135}	0.55
Zr^{95}	< 0.01	Cs^{136}	0.96
Zr^{97}	< 0.01	Cs^{137}	0.23
Mo^{99}	< 0.01	Ba^{140}	0.25
Ag^{111}	32.	Ce^{143}	0.17
Cd^{115}	50 (assumed)	Ce^{144}	0.17
Sn^{121}	27	Nd^{147}	< 0.01
Sn^{125}	12	Eu^{156}	1.6
Sb^{127}	8.5	U^{235}	< 0.01
I^{131}	1.8		

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External Flux Monitors in E.P. IV

A number of nickel foils were exposed to the neutron flux above the Phoebus-1A reactor core during the full-power test. Rabbits, containing the foils, were fired into and out of position by remote control at various times during the run. One foil, called the integral foil, was exposed during the entire run. The amount of Co^{58} produced in each foil by neutron activation (via the reaction $\text{Ni}^{58}(\text{n}, \text{p})\text{Co}^{58}$) is assumed to reflect the relative number of fissions generated in the reactor core during the exposure of that foil. Results are given in Table 12 as fractions of total fissions generated during each exposure period.

Table 12. Fraction of Fissions Generated During Various Periods in Phoebus-1A

<u>Foil Number</u>	<u>Foil Exposure Period (sec)</u>		<u>Fraction of Total Fissions Generated During Exposures</u>
	<u>Begin</u>	<u>End</u>	
1	0	22484.3	0.0172
2	22487.3	22562.6	0.0705
3	22565.3	22620.8	0.0770
4	22664.3	22778.3	0.1725
5	22790.3	22960.5	0.2560
6	22963.9	23192.9	0.3357
Integral	Entire Run		1.0 (by definition)

Experimental Neutron Detectors in E.P. IV

Phoebus-1A was instrumented with three experimental neutron detectors. Two of these were U^{235} fission ion-chambers mounted in an Al block on the exterior of the convergent section of the nozzle. The objectives of the test were to determine (a) whether or not these chambers could function properly under the conditions of vibration, temperature, and radiation at this location, and (b) if the radiation inducing current in the chamber at this location is proportional to reactor power.

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The third detector was a compensated boron ion-chamber which was located 72 ft from the reactor on top of the wall protecting the tank farm on the east side of the test cell. It was desired (a) to operate a B chamber at a current in excess of 10 mA and to observe any degradation that might occur, and (b) to determine if the detector operated in a linear fashion at this high current. It had been intended to move this detector, or a similar one, behind the Neutronics Penthouse on one of the restarts and measure only the scattered neutrons.

Table 13 shows the currents and calculated powers and their errors (with respect to the early calculations of thermal power). Data are given for 22600 sec at the start of the full-power hold.

Table 13. Currents and Calculated Powers from Neutron Detectors

	<u>Current, A</u>	<u>Power, MW</u>	<u>Error (%)</u>
Thermal Power	--	1090	-
Nozzle A (Reuter-Stokes)	2.97×10^{-4}	1349	24
Nozzle B (Westinghouse)	3.7×10^{-4}	1567	44
Boron Comp. (General Electric)	14×10^{-3}	1103	1
Linear No. 1	5.27×10^{-5}	1055	3

Both nozzle chambers survived the run. They indicated a slow cyclical variation in current that can be partially correlated with the temperature variation in the support block on the nozzle. The current readings tended to be somewhat higher than the other chambers; this may be due either to the moderating effects of H_2 in the nozzle or to the temperature effects on top chambers.

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It is perhaps significant to note that, at time 22400 sec, the error between the nozzle chambers and selected linear power is negligible. At this time the fission chamber temperature was 100°F. The coldest temperature measured, -90°F, was at 22510 sec when the largest error occurred.

The high-current B chamber operated in a linear fashion throughout the run and tracked linear and thermal power closely.

R-MAD Operations

The Phoebus-1A reactor was returned to the disassembly bay of the MAD Building on June 29. The nozzle was removed and photographs were taken of core damage. On July 6, the reactor was moved to the R-MAD dump to await completion of the NRX-A3 disassembly and preparation for Phoebus-1A disassembly.

The reactor was retrieved on August 9, and nearly normal procedures were followed for its removal from the test car. On August 13, the core was transferred to the upper disassembly bay for cluster removal and disassembly of the elements. The disassembly was completed on August 25, and two casks of elements were shipped to LASL shortly thereafter.

Normal procedures were not possible during the core disassembly because many elements, or portions of elements, had been expelled immediately after the full-power run. In addition, the overheating of the core resulted in extensive fusion of elements to each other. This required a large amount of grinding to separate the fused portions in order that individual elements could be separated for photography and postmortem studies. The second or final version of the automatic photography system was employed to photograph individual elements. As stated earlier, this system performed in a satisfactory manner; during some periods, however, malfunction of the logic system resulted in improper designations for individual photographs.

Test Cell Wall Heating

Thermocouples imbedded in the face of the test cell measured the temperature increases at various depths during the Phoebus-1A full-power

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run. The results are given in Table 14. Only the two deepest thermocouples appeared to have an adiabatic temperature rise during the full-power

Table 14. Maximum Temperature Increases in Test Cell wall

<u>Thermocouple Depth, in.</u>	<u>Material</u>	<u>Temperature Rise, °R</u>
0.34	Concrete	167
0.75	Concrete	Thermocouple failed
1.62	Concrete	152
3.12	Concrete	127
3.44	Iron	143
3.75	Iron	143
4.06	Iron	143
9.09	Concrete	46
15.12	Concrete	16

hold. The data from the first three thermocouples in concrete fit very well to curves of the form $\Delta T = A + B(1 - e^{-Ct})$, where ΔT is the temperature rise and t is time at the full power hold. This suggests heat losses to a constant temperature sink. The reinforcing bar temperatures follow a curve which parallels the temperatures in the nearby concrete and which indicates significant heat loss into the concrete (Fig. 26).

Initial rates of temperature rise were determined from the curve fits for the 0.34-, 1.62-, and 3.12-in. depths and from the data for the 9.09- and 15.12-in. depths. Using a specific heat of 0.156 Btu/lb-°R, the heating rates calculated for the full power portion of the run are given in Table 15. The curve fits also allow for some degree of extrapolation of the data.

Maximum temperatures achieved during the Phoebus-1A run and those anticipated from a 15-min run are shown in Fig. 27. It can be seen that the 200° temperature limitation often imposed to avoid dangers of

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Fig. 26. Temperature buildup in test cell face during Phoebus-1A, E.P. IV.

Fig. 27. Temperature increases at various depths in test cell face.

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Table 15. Heating Rates in Test Cell Wall

<u>Thermocouple Depth, in.</u>	<u>Heating Rate in Concrete, W/g</u>
0.34	0.133
1.62	0.109
3.12	0.0780
9.09	0.0257
15.12	0.0089

concrete spalling would be reached in 15 min with this reactor. Spalling of concrete from the test cell face was observed after the Phoebus-1A test; however, this is believed to have been caused by the hydrogen flame from the belly band leak.

Anemometers

Based upon pre-run calibrations, the three anemometers mounted on the Phoebus-1A test car gave the following wind velocities:

<u>Anemometer Location</u>	<u>Orientation</u>	<u>Air Velocity, ft/min</u>
Station O, 4 in. from P.V.	Vertical	300 to 400 upward
Station O, 12 in. from P.V.	Vertical	0 during the run
Station O, 12 in. from P.V.	Radial	300 to 400 inward

The data gave no reason to believe that any of the anemometers failed during the run; however, no post calibration checks have yet been performed because of the activation of the transducers.

Thermal Radiation Measurements

Thermal radiation measurements made on the 120-ft tower during Phoebus-1A, E.P. IV agree within 5% of those measured during the Kiwi-B-4E-301 test. The following heating rates were obtained with asymptotic calorimeters:

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<u>Elevation, ft</u>	<u>Heating Rate, W/in.²</u>
0	6.96
60	13.2
120	19.9

These heating rates were less by approximately the ratio of LH₂ flow rates during the hold step.

Water cells at the base of the tower showed a thermal radiation reduction of 0.71 by means of $\frac{1}{8}$ -in. of water; if exponential absorption is assumed, an absorption coefficient of 2.7-in.⁻¹ is obtained. Thus, 0.26 in. of water would reduce the thermal radiation by a factor of two. However, there is some evidence to indicate that the absorption curve follows the form $\exp(-A\sqrt{d})$, where d is the water thickness. This would give a coefficient of 1.25 in.^{-0.5}, and 0.18 in. water would be required for reduction by a factor of two in flux level.

The optical scanner on the C.P. roof showed a roughly gaussian distribution of radiation from the H₂ plume with the peak at about 150 ft above the reactor. A similar distribution was obtained from measurements on the 420 ft tower. This distribution has been applied to calculations at points on the 120 ft tower with greater success than using the flat distribution previously assumed.

Decontamination

It was estimated that approximately 10-20% of the Phoebus-1A core was ejected due to the loss of coolant and subsequent overheating of the core. The debris consisted principally of fuel pieces 1-6 in. long, cluster blocks, and miscellaneous fine particulate material. The pattern had a radius of roughly 300 ft with a lobe extending perhaps twice that far in a NW direction. After about 3 weeks of decay time, during which various possible remote or shielded cleanup techniques were evaluated, it was decided that manned pickup of large fuel pieces was feasible, and in fact would be the most effective means of reducing the gross contamination level by about an order of magnitude. This approach was followed and required a radiation exposure of the order of 100 mrem.

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The foregoing effort permitted the application of standard vacuum, sweeping, wash-down, and earth removal techniques to be used with relatively little exposure investment to complete the Test Cell C decontamination. Approximately 10,000 cu. yards of dirt were spread on the west side of the test cell to reduce the radiation intensity, as well as to prepare for the placement of the new LH₂ dewars and hot-water tank.

TEST CELL C

Modifications and Additions

General

As a result of the Phoebus-1A test, the facility and reactor schedules have been revised. It is now planned to complete the facility modifications before the Phoebus-1B tests. This means that the emergency high-pressure dewar (see below) will be installed and that the NFS-3 pumping system will be located in the new pump room prior to Phoebus-1B. The new million-gallon LH₂ storage will also be available for the test. Contract work and installation is scheduled for completion by March 1, and system checkouts should be complete by May 15, 1966. The net effect of the revision is to delay Phoebus-1B testing by 1 to 2 months and to advance facility completion by about 3 months.

During the past quarter, construction work fabrication, and related planning, engineering, and procurement have been in progress. The status of the more important areas of activity is reported below.

First Construction Package - LH₂ Dewars and Hot Water Tank

Erection of Dewar C is approximately 75% complete. Erection of Dewar D was started during the week of June 7 and is approximately 50% complete. Erection of the water tank is 90% complete. The tentative schedule for moving the vessels from the remote erection site is revised

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as follows:

1. Dewar D to Test Cell C - no change from October 18.
2. Dewar C to Test Cell C - change from October 25 to November 2.
3. Water tank to Test Cell C - change from October 11 to September 14.
14. The contractor has been requested to complete work on the water tank by October 30 to enable PMI Corp. to complete the water system piping sooner.

Acquisition of all of the hardware for the LH₂ dewar instrumentation racks has been completed except for some miscellaneous fasteners. Fabrication drawings for these items are 80% complete. Included will be the "fathometer" to replace the capacitance level gauges.

Second Construction Package - Site, Piping, and Electrical Systems

The contractor moved out of the test cell area on June 18 and returned on August 23 for a total of 66 days lost compared to the scheduled 45 days. One additional day was lost due to testing on June 10. All work originally scheduled during the first phase of construction plus the additional work associated with the LN₂ dewars and high-pressure gas bottles was essentially completed.

Government-Furnished Equipment

Vacuum-Jacketed Pipe: The 3-in. LH₂ fill lines will be shipped starting September 1. The balance of this piping will be shipped by September 27. Associated Piping has been given an additional order to furnish the 4-in. LN₂ supply line with delivery scheduled by mid-December 1965.

Valves: Approximately 50% of the valves required for the LN₂ system have been obtained from government surplus. Data sheets for the remaining valves have been written and are presently on order. A complete list of modification valves has been compiled and placed on an IBM card deck and is kept current weekly. This list will be used not only for type and location of the particular valve, but will contain certain pertinent information to assist in the maintenance of spare part inventories.

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Flow Systems

Flow Measurements: The 10-in. LH₂ pump inlet venturi has been fabricated and delivered to the piping contractor (Associated Piping) for incorporation in the vacuum jacketed piping. It now appears as if a change in criteria is to be made for this item, upgrading the flow rate from 350 to 400 lb/sec. The redesign of this venturi has been completed and the drawings executed. A cost figure is being obtained from the contractor for the modification.

Liquid Nitrogen System: The three 28,000-gal dewars obtained as surplus have been delivered and mounted on their foundations at Test Cell C. Complete piping drawings for connecting them to the facility have been completed. The contractor (PMI) has been awarded an addition to his contract for installation of the piping for the LN₂ dewars and high-pressure gas bottles. Drawings for piping in the flow control room have not been released. Conversion of the experimental LH₂ heat exchanger into the LN₂ vaporizer by ACFI is tentatively scheduled to be complete on October 15, 1965.

Work is underway to purge the dewars and to perform vacuum tests on these vessels. The original vacuum pumps have had to be replaced as they lasted only about 10 h each, after startup.

The Cryo-Sonics pump vaporizer that is to be used for bottle charging has not yet been delivered. This item was to have a 10-week delivery date and was due for delivery by May 11, 1965.

In the Phoebus reactor tests, after the initial cooldown interval (approximately 1 h) during which H₂ will be used, the remainder of the fission product energy will be removed using GN₂. The GN₂ will be supplied at 200°R produced by the LN₂-H₂O heat exchanger. This system is designed to provide GN₂ flow rates of 25 lb/sec. The cooling will be done in a pulsed manner, the frequency and duration of the pulses varying as the cooldown proceeds.

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The three 28,000-gal dewars will supply the LN_2 for post-run cooling. The vaporizer is to be made by ACFI, drawing largely on information obtained from the experimental H_2 heat exchanger. The design of the vaporizer and associated facility interconnecting piping has been completed and transmitted to the contractors.

Water- LN_2 Heat Exchanger System (Turbine Drive System)

Design effort on the full-scale heat exchanger by ACFI is now nearing completion. Construction materials have been placed on order and some items have been received. Fabrication of the structural steel supports and shop work on the Al inner parts have already begun. The analysis of the revised design (wall thickness reduction of $\frac{1}{4}$ in. and fin height reduction from $1\frac{1}{2}$ in. to 1 in. to reduce thermal stresses and reduction in overall length to 320 ft) is being continued. Tentative date for shipment of this exchanger has changed from October 15 to December 7. A revised erection procedure is necessary to enable PMI to proceed with their work.

In tests with the experimental heat exchanger (LA-3280-MS, p. 56; LA-3341-MS, p. 52), two 80-ft passes were completed. The heat transfer coefficients averaged 90% of those calculated from the Dittus-Boelter equation in the section containing the twisted tape swirl inducer and 65% in the section without a swirl inducer. Fin efficiencies were 16% when no ice was present. As the extent of ice cover increased so did the fin efficiency, reaching 100% when the fins were completely covered with ice. Pressure drops were 2.8 times the predicted values in the pass containing the swirl inducer and 1.3 times the predicted values in the other pass.

The experimental heat exchanger used for these tests is currently being refitted for use as a LN_2 vaporizer.

Reactor Shield

As a consequence of the Phoebus-1A results and the revised schedules which include the possibility of three reactor duration tests

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(Phoebus-1B, NRX A-5, and Phoebus-1C) at Test Cell C in the latter half of 1966, it has been decided to provide a reactor shield for Phoebus-1B rather than to wait until the Phoebus-1C test. The purpose of such a shield is primarily to reduce neutron activation of the facility environs and secondarily to reduce γ -ray heating in the front wall of the test cell.

The Phoebus-1 shields were based on Phoebus-2 shield design which consisted of a water-cooled cylindrical shell around the reactor; the flow passages are B-loaded Al tubes. The cooling water was provided by the exit water from the LH_2 - H_2O heat exchanger. Schedule considerations have caused a review of this concept and a proposal has been made to use a borated water solution in lieu of the above. Initial study shows that the present 150,000-gal ground storage tank and flow system would be adequate for Phoebus-1 reactor shields. Modifications to the system would include the addition of a water pump, for which foundations and mounting bases already exist, to bring the pumping capability to approximately 2400 gpm, and provision to keep the borated solution uniform.

Post-run Cooling of Reactors

The need for a high-pressure LH_2 dewar system for emergency and post-run cooling was emphasized by the experience of the Phoebus-1A test. It has been decided to provide such a system for the remaining Phoebus-1 reactors as well as for Phoebus-2 as originally planned. The dewar size has been set at 8000 gal at a working pressure of 750 psi. The Chicago Bridge and Iron contract for Dewars C and D has been expanded to furnish this vessel, with a completion date of March 18, 1966.

Using the MIDAS code and typical power profiles, calculations have been made to determine the characteristics of an emergency shutdown using a high-pressure dewar. Typical results are shown in Fig. 28. The calculations indicate that about 5000 gal of LH_2 are required to cool the reactor to the point where the old dewars can supply further LH_2 . An initial pressurizing gas volume of about 2000 gal is required. An 8000-gal dewar should be acceptable for this service and provide an adequate margin of safety.

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Acquisition of six 53 ft³ high-pressure gas storage bottles to be used as a warm gas ullage space for the high-pressure dewar has been initiated. These bottles were declared surplus by the Air Force upon the deactivation of some Atlas D missile installations.

Control Room Modifications

Control Room (C.R.) rack layout modification has begun. The two services racks, 25 and 26, have been moved against the wall of the C.R. to permit placement of three additional racks in this area. The computer racks will be located next to the C.R. Sanborns. Relocation of the EEM and CSM consoles will require modification of the C.R. main entrance area to include part of the present hall space.

The C.R. layout shown in Fig. 29 reflects the operational philosophy and the number of operators required. The cooldown operation will take place at racks 6 through 9. The N₂ cooldown controls will be located in rack 6, Dewars A and B and gas bottle controls in rack 7, mixing chamber control in rack 8, and the high-pressure dewar controls in rack 9. Racks 11 through 24 will retain their present functions, i.e., the pump monitor, program, neutronics, and control room Sanborn operators will be located at these racks. Controls for Dewars C and D, the LH₂ heat exchanger, and the water system will be located in the three additional racks next to the services racks.

Control Room Automation

A computer (Quarterly Report LA-3341-MS, p. 50) which is the heart of the planned operations control system, has been ordered from the Computer Control Corporation, Model DDP-116, with delivery currently scheduled for late January 1966.

Programming methods and philosophy have been under study. The objective will be to provide the greatest flexibility while insuring that the computer is always operating on that function or operation which

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Fig. 28. Calculated profiles for emergency shutdown using a high-pressure dewar.

Fig. 29. Control room floor plan.

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currently is the most important. This philosophy is one that both General Electric and Honeywell have utilized successfully, although considerable modification and sophistication will be required to suit the specific application at NRDS. Specific functions (computations) will comprise subprograms which will be called by the main program in an order dictated by desired computation rate and assigned priority. External interrupt capability will be fully utilized.

The planned initial application will be of on-line monitoring. Real time computations will be performed, resulting in information presented to the operating team which is not readily obtainable from existing C.R. indicators. By scanning both facility and reactor parameters and providing computations which would be difficult to implement with conventional analog circuitry, the computer should be a valuable means of insuring the safe operation of the facility and reactor. Furthermore, the ability to select and display various parameter profiles, such as azimuthal or radial reactor station temperature, should make the cathode-ray tube readout a useful tool in core structure as well as facility monitoring.

A logic sequencer rather than the DP-116 will be used to automate those portions of the checklist which are standard or routine and to facilitate parallel system operations. Typical operations to be automated are header and dewar pressurization, and the chilldown of the cryogenic systems prior to the actual run phase. Each system involved will have its individual logic sequencer. A standard logic chassis will be developed with one or more such chassis interfaced with the system's control chassis. Any element within an automated system, e.g., a valve, will be removed from logic control by operator activation of that element in the conventional manner. If the logic actuation of a system element is bypassed in logic sequence, capability will be provided for reentry into the sequence at any subsequent instruction. The planned inputs and outputs

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of the logic sequencer are depicted in Fig. 30. Solid state logic has been under evaluation and trial chassis fabricated and tested.

Neutronics

The plans to place water shields around future Phoebus-1 and -2 type reactors necessitate radical rescaling of the neutronics system, and the probable elimination of detectors inside the present water tank entirely. Various alternatives, such as widening the dynamic range of the logarithmic amplifiers to permit use of a fixed position detector, two fixed position detectors of different sensitivity, and taking advantage of the reactor shield as an attenuator in place of the present water tank, are being considered.

Detector research is in progress. Experiments on Phoebus-1A have been described earlier in this report (p. 68), and four experimental chambers will be tested on the upcoming NRX-EST reactor.

Data Systems

A major rearrangement of ELR (test cell basement) equipment is in progress as a result of the Test Cell C expansion. The TV system is being moved to the Fill Station, to make room for new equipment, and installation is about 30% complete. The wide band system has been relocated in the ELR and is approximately 50% reinstalled.

Fig. 30. Inputs and outputs of logic sequencer.

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The narrow band data system relocation, modification, and expansion have been planned and will be under way soon. Four hundred Neff amplifiers have been ordered to replace the existing Video Instrument amplifiers. Partial delivery of these units is to begin in October, with a promised completion date in November 1965. EG&G is building an instrument for use in acceptance testing of the Neff amplifiers and for routine maintenance thereafter.

MISCELLANEOUS ACTIVITIES

Turbopumps

The first phase of the NFS-3A Single Mode ("E" blade) Pump testing was completed during the last week of August. A total of 18 tests were run on the first "E"-bladed pump, including four successful stall recovery tests at pump speeds of 10,000, 15,000, 20,000, and 25,000 rpm. Disassembly of this pump, which had been run in excess of 1300 sec, showed only moderate wear to the bearings and bearing surfaces, with the exception of a cracked inner race of the aft bearing. Neither the cause of the crack nor the test in which it developed has yet been determined. This first pump is now being converted to a duplex bearing configuration and should be available for further testing prior to completion of the two deliverable Mk-25 turbopumps. The second "E"-bladed pump has been installed in CTL-5 at Santa Susana and has successfully undergone its first test at 34,000 rpm.

Testing of the five-stage turbine has shown the performance to fall well within the expected limits. S/N ROOLR had been oversped to approximately 39,500 rpm during a system test. Subsequent disassembly and inspection revealed the turbine to be in excellent condition.

Rocketdyne has available and ready for testing, when time and test schedule allow, a Mk-9 pump with soft-mount bearing and increased friction damping. It was reported previously that tests on this soft-

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mount configuration would be run during this quarter. However, because of hardware delays and a full schedule of "E"-bladed pump testing, the soft-mount testing has been postponed.

Assistance to NTO

The Nerva Test Organization (NTO) was supported at the R-MAD Building for NRX-A3 disassembly operations. The reactor was returned from Test Cell A to the MAD Building on June 2, and disassembly was completed on June 22. This assembly made use of the first version of the automatic photography system, which performed very well in providing photographs of all NRX-A3 elements for later close visual examination. The postmortem of this reactor was completed on July 27 in preparation for the Phoebus-1A test, except for work in two hot cells which were not required for the Phoebus operations.

Nondestructive testing has included routine radiography of NRX-A3 reactor components during postmortem operations, as well as radiography of NRX-A4 (EST) car and plumbing hardware. In addition, radiography has been conducted on the plumbing at Test Cell C in connection with the current modifications. A total of 524 exposures have been made on 188 welds.

Calculations were performed for NTO to determine the facility GN_2 flow capability and the temperature effect upon gas storage bottles due to rapid blow-down. Suggestions were made as to the location of instrumentation to verify these calculations.

Calculations were also performed on the LH_2 system to determine what modifications would be required to deliver 75 lb/sec of LH_2 to the turbopump for a full duration run. Assistance was furnished in connection with specifications for both a N_2 and H_2 gas converter to enable NTO to complete purchase requests for several of these items.

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Equipment Testing Laboratory

Installation of two 1200-ft³ gas storage vessels was completed. Piping, instrumentation, and control drawings are complete and await approval of construction funds. All the valves are on order for this installation. The design of a 2-in. water flow system in the flow bay for smaller components and lower pressures was completed. Construction has begun on this system. Modifications for an increased hydraulic oil flow capacity system were started. Design of a monorail hoist handling system and installation of a thermocouple reference junction were completed.

Pressure and leak tests were conducted on 106 valves of various types and sizes, six pressure gauges, 27 hose assemblies, two pressure regulators, a welded pipe assembly, and a thermocouple probe assembly.

Evaluation flow tests, using water, were conducted for a 6-in. ball valve, a 3-in. Annin control valve, a 4-in. plug-check valve, and two 3/8-in. solenoid valves. Nitrogen gas flow tests were completed on an 8-in. ball valve, and a gas check valve. Improved calibrations ($\pm 0.25\%$) of two 8-in. water system turbine flow meters were completed.

Four rotameters were calibrated. Bubble tests were conducted on six hydraulic filter elements (pore size determinations). Recalibration of the 5-ft³ storage tank was completed to a higher accuracy ($\pm 0.03\%$). The surge tank will be used for accurate small gas flow meter calibration and as a transfer standard for calibration of the 1200-ft³ storage vessels. Experiments using a turbulence fluid-amplifier "logics laboratory" were conducted for familiarization with these devices. A data storage and indexing system for ETL test data was completed.

Hydrogen Flame Studies

In an attempt to predict the heating of objects surrounding an operating Phoebus reactor as a function of H₂ flow rate, measurements are being made of the spectral brightness at various wavelengths and

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at various points in small H_2 flames. With these brightnesses, the incident flux at any point around the flame can be found by integration. This flux and the heating it produces can be compared with the heating during past Kiwi and Phoebus tests and an estimate made of heating with increased H_2 flow rates.

The basic method for measuring flame brightness is to make spectrograms of H_2 flames and convert film densities to spectral brightnesses. The detailed experimental procedure has been established, programs for data reduction have been completed, and instructions for their use have been written. The necessary equipment has been obtained and set up. Data have been taken using a calibrated W lamp and processed into a data deck which will be used to convert densities of films taken of H_2 flames into spectral brightnesses.

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IV. FUEL ELEMENT FABRICATION, TESTING, AND DEVELOPMENT

TESTING OF GRAPHITE FUEL ELEMENTS

Evaluation of Glued Tips of Fuel Elements

The fuel elements used in Phoebus-1A were of the "glued-tip" design having a tenon on the loaded portion. As part of the evaluation of the strength and leak tightness of this joint, 23 samples of glued tips from Phoebus-1A core production were evaluated for He permeability and then tested to failure in tension. Nearly all the joints tested in tension failed at the unrelieved base of the machined tenon. The tensile strengths averaged 1300 psi over a range of 652 to 2811 psi, somewhat weaker than for elements from Lots 217 and 218, the selected strength references. While joint leak rates varied from 0.1 to > 22 liter/min at 25 psi He pressure, there was apparently no correlation with strength properties. More than 80% of the joints leaked less than 0.2 liter/min.

Hydrogen Corrosion Tests of Phoebus-1B Preproduction Fuel Elements

Preproduction elements manufactured at UCNC (Y-12) for the Phoebus-1B reactor were tested for corrosion in H₂ for quality evaluation and coating furnace certification. Fuel elements from the Y-12 coating furnaces 7S, 8S, and 9S were tested using RPT-2400°C-30 min conditions which simulate 5000°R exit gas Phoebus-1 reactor conditions. Summaries of test results for coating furnaces 7S and 8S are given in Tables 16 and 17.

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Table 16. Phoebus-1B Hydrogen Corrosion Tests of
Preproduction Elements from UCNC (Y-12) Coating Furnace 7S

<u>Batch No.</u>	<u>Completed RPT-2400-30</u>	<u>Average Loss, g</u>	<u>Average Loss Rate, g/min</u>
BCLX-36	3 of 4	11.9	0.40
BCLX-55	3 of 4	14.4	0.48
BCLX-57	4 of 5	11.3	0.38
BCLX-60	2 of 2	13.9	0.47
BCLX-65	1 of 2	11.0	0.37
BCLX-66	2 of 2	11.8	0.40

Table 17. Phoebus-1B Hydrogen Corrosion Tests of
Preproduction Elements from UCNC (Y-12) Coating Furnace 8S

<u>Batch No.</u>	<u>Completed RPT-2400-30</u>	<u>Average Loss, g</u>	<u>Average Loss Rate, g/min</u>
BCLX-46	3 of 4	17.1	0.57
BCLX-48	2 of 4	12.5	0.42
BCLX-51	4 of 4	12.8	0.43
BCLX-52	1 of 2	16.1	0.54
BCLX-56	0 of 2 (stopped because of loss of overpressure)		

Furnace 7S has been certified for production status. The average weight loss for fuel elements in batch BCLX-55 includes one high value of 22.3 g. One element from BCLX-57 was tested for life at RPT-2400°C and in 38 min it lost 22.1 g at a rate of 0.58 g/min.

Furnace 8S was placed on production status. The average weight loss of fuel elements in batch BCLX-46 includes a single high value of 24.9 g. Life test at RPT-2400°C of an excellent element from BCLX-48 gave the following results: 43 min, loss = 15.5 g and loss rate = 0.36 g/min. However, a breakdown in the furnace occurred during the first

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production run. Repairs and checkout are essentially completed and coated fuel elements will be available soon for recertification of this furnace.

Coating Furnace 9S is in the process of being certified. The latest corrosion tests resulted in 16.8 g loss in RPT-2400-30 min (0.56 g/min).

Pinholes were observed in 44% of the corrosion-tested preproduction elements. No significant difference was found between the furnaces in frequency of pinhole occurrence.

Permeability of Phoebus-2 Zepo Fuel Elements

Fuel elements produced in Lots 236, 238, and 240 through 247 were intended primarily for the Phoebus-2 Zepo core but represented several production development experiments involving gluing techniques, curing temperatures, and tip stock compositions. The glue employed consisted of Varcum binder with 33% added 1008 flour (-400 mesh). All elements were graphitized to 2250°C after gluing. Helium permeability tests were conducted using the procedure described in Quarterly Report LA-3280-MS, p. 77.

It appears that curing temperatures below 430°C produce tighter joints and that there is no difference between joints glued in the baked state and those made with graphitized elements. The addition of 75 g of wood flour per 6 kg of dry C in the extrusion mix for the unloaded tip stock did not appreciably affect the leak rate of the region containing the joint. When 150 g of wood flour were added, the average leak rate approximately doubled but this may well have been due to the greater porosity of the resulting tip stock rather than to greater leakage in the glue joint. In general, the joints of the Phoebus-2 Zepo lots were not as tight as some of the earlier experimental lots, with only 38% meeting an arbitrary standard of 0.05 liters/min.

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Damage to Fuel Elements by Load Cycling

It is known that graphites suffer some damage when loaded to a large fraction of their breaking strength. An experiment is being done to determine the magnitude of this phenomenon for the first cycle of axial compressive load on Phoebus fuel element material and the effect of thermal annealing.

Seven standard $1\frac{1}{4}$ -in. long fuel element samples were cycled at room temperature several times in compression from 0 to 3500 lb ($\sim 10,300$ psi) at a linear ramp load rate of approximately 1000 lb/min. After removal of the strain gauges, the specimens were then heated in He to 2350°C over a 15-min period; held at 2350 for 30 min, and finally cooled down over a 20-min period; no effort was made to control the cooldown rate. Following the annealing process, the samples were instrumented as before and recycled to as high a load as their weakened condition would permit (usually 2750 to 3000 lb). The room temperature stress-strain relationships were continuously recorded and compared with the results obtained prior to the annealing operation.

Typical "before and after" load-strain plots are shown in Fig. 31. The secant Young's modulus, taken over an arbitrary interval of 3000 $\mu\text{in./in.}$ strain,

Fig. 31. Typical load-strain plots for Phoebus fuel elements before and after annealing.

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is presented, together with other pertinent data, in Tables 18 and 19, the nomenclature for which is given below. Some idea of the bending present before and after annealing can be obtained by comparing ϵ_1 max with ϵ_2 max; ideally, they should be equal.

Nomenclature for Tables 18 and 19

E_1	Young's modulus, side 1
E_2	Young's modulus, side 2
E_{av}	Average of Young's modulus for sides 1 and 2
ϵ_1 max	Max. strain on side 1 of specimen before annealing, second cycle
ϵ_2 max	Max. strain on side 2 of specimen before annealing, second cycle
ϵ_1^1	Max. strain on side 1 of specimen after annealing, second cycle
ϵ_2^1	Max. strain on side 2 of specimen after annealing, second cycle
P max	Max. load on specimen before annealing
P^1	Load on specimen at strain of ϵ_1^1 and ϵ_2^1
e_a	See Fig. 31
e_b	See Fig. 31
σ_{ult}	Ultimate compressive stress of sample

Unequal values of ϵ_1 and ϵ_2 indicate bending of the sample.

Based on a compressive stress value of $13,194 \pm 829$ psi for loaded elements from Lot 7 and previous cyclic experiments, it appears that the compressive strength of the material studied is significantly reduced by the heat treatment. Although the character of the stress-strain curve before and after heat treatment is the same, the strain at any given load is significantly higher. That is, the specimens become considerably "softer" after heat treatment.

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Table 18. Mechanical Properties of Unloaded Fuel Elements

Property	Specimen 1686-AA-67		Specimen 1686-AA-65		Specimen 1686-AA-83	
	Before Annealing	After Annealing	Before Annealing	After Annealing	Before Annealing	After Annealing
E_1 (10^6 psi)	1.97	1.72	1.90	1.66	1.72	1.72
E_2 (10^6 psi)	1.79	1.56	1.80	1.72	2.02	1.66
E_{av} (10^6 psi)	1.88	1.64	1.85	1.69	1.87	1.68
ϵ_1 max (μ in./in.)	7250	NA	7750	NA	8850	NA
ϵ_2 max (μ in./in.)	7850	NA	8150	NA	6350	NA
ϵ_1^1 (μ in./in.)	NA	7900	NA	8050	NA	7750
ϵ_2^1 (μ in./in.)	NA	8750	NA	7950	NA	7950
P_{max} (lb)	3500	NA	3500	NA	3500	NA
P^1 (lb)	NA	3000	NA	3000	NA	3000
e_a (μ in./in.)	NA	1650	NA	1500	NA	1500
e_b (μ in./in.)	1100	NA	1275	NA	1000	NA
Lub used ?	No	Yes	Yes	Yes	No	Yes

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Table 19. Mechanical Properties of Bead Loaded Fuel Elements

Property	Spec. No. 7-45-5251		Spec. No. 7-45-5239		Spec. No. 7-45-5237		Spec. No. 7-45-5253	
	Before Anneal	After Anneal	Before Anneal	After Anneal	Before Anneal	After Anneal	Before Anneal	After Anneal
E ₁ (10 ⁶ psi)	1.97	-	1.63	1.37	1.86	1.32	1.73	1.66
E ₂ (10 ⁶ psi)	1.83	-	2.10	1.62	2.10	1.83	1.87	1.46
E _{av} (10 ⁶ psi)	1.90	-	1.86	1.49	1.98	1.58	1.80	1.56
ε ₁ max (μin./in.)	7300	Sample Broken	8250	NA	8100	NA	8050	NA
ε ₂ max (μin./in.)	9450		7150	NA	6900	NA	7950	NA
ε ₁ ¹ (μin./in.)	NA		NA	9650	NA	9250	NA	9050
ε ₂ ¹ (μin./in.)	NA		NA	8250	NA	8450	NA	9100
P max (lb)	3500		3500	NA	3500	NA	3500	NA
P ¹ (lb)	NA		NA	2750	NA	2750	NA	2750
e _a (μin./in.)	NA	-	NA	1850	NA	1900	NA	2010
e _b (μin./in.)	1010	-	950	NA	960	NA	1000	NA
Lub used ?	Yes	-	Yes	Yes	Yes	Yes	Yes	Yes
σ ult (psi)	-13,194±829	-	-13,194±829	-10,263	-13,194±829	-10,409	-13,194±829	-10,557

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The data in Fig. 31 and Table 18 show considerable first-cycle damage in the specimens both before and after annealing. In both cases, the samples do not suffer significant additional strain damage upon repeated cycling, i.e., the initial first-cycle damage is retained within the material. The 2350°C annealing treatment appears to remove this first-cycle, load-induced damage initially. However, in the case of the bead loaded elements, the heat-treated material is left approximately twice as sensitive to subsequent first-cycle damage. This trend is present in the unloaded samples but is not as pronounced.

Fuel Element Thermal Stress Experiments

In a recent report (LA-3323-MS), the progress is reviewed of an experimental program which is attempting to establish the power density/thermal stress limits for reactor fuel elements. The apparatus and experimental techniques developed, methods of analysis, and results to date are presented in the report. The work has been motivated by the desire to increase the power density capabilities to levels approaching those proposed for Phoebus-2. Such an experiment is currently planned for the Phoebus-1B reactor. The postmortem inspections for the Kiwi-B-4E-301 (see LA-3185-MS and LA-3299-MS) reactor did not reveal any core damage that could be attributed to thermal stress cracks or fractures and therefore indicated a safe margin for the 35-in. diam core at ~1100 MW.

The main results presented in the report, which is chiefly concerned with oxide-loaded specimens, may be summarized as follows:

1. The experimental arrangement subjected the fuel element specimens to more severe thermal stress conditions than the reactor when compared on a direct power density basis due to transverse heat flux by radiation from the specimen outer surface.
2. Electrical resistance heating at the required high current densities is possible.

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3. Fractures and cracks could be produced in the specimens.
4. Thermal and heat transfer analysis techniques similar to those used for reactor core analysis agreed quite well with the experimental data.
5. Preliminary results for the few bead-loaded fuel element specimens tested thus far are encouraging for the increased power densities planned in future reactors.

After some modifications of the experimental equipment the experiments will be continued with specimens of bead-loaded material of current production.

Room Temperature Postmortem Mechanical Strength Properties

The average compressive and flexural strength profiles of fuel elements from the Kiwi-B-4E core postmortem were presented in a previous Quarterly Report (LA-3280-MS, p. 24). It was shown that while exposure to the reactor environment weakened these elements at locations subject to corrosion, the strength of elements at the inlet ends was apparently enhanced by the reactor run. Figure 32 shows typical average pre-test and postmortem

Fig. 32. Strength profiles of pre-test and postmortem loaded fuel elements from Kiwi-B-4E.

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strength profiles for 450 mg U/cm³ loaded fuel elements. Detailed analysis of these data is complicated by the existence of a nonuniform pre-test strength profile and the fact that pre-test data are obtained prior to the leaching and coating operations and in a different facility from that used for the post-test evaluation.

The effect of the pre-test strength profile has been eliminated by careful lot-matching of the existing data on a sample-for-sample basis by a computer technique. The results yield a "reduced" strength profile showing the average percent retained strength at each sample location. These profiles are shown for each of six different fuel element compositions in compression and flexure in Figs. 33 and 34, respectively. The corrections for the weakening

Fig. 33. "Reduced" strength profiles of fuel elements in compression.
Fig. 34. "Reduced" strength profiles of fuel elements in flexure.

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effects of subsequent processing and the necessary differences between the remote and conventional testing operations are too small to evaluate quantitatively but should displace these curves upward somewhat less than 10%.

In general, exposure to the reactor environment has significantly strengthened the elements at the inlet end. Retained element strengths fall to a minimum at approximately Station 25, rise again, and fall once more at the exit end. The 170 mg U/cm³ elements appear to reach their strength minima farther upstream at approximately Station 20. These elements were located at the extreme perimeter (Fig. 35) and are believed to have been significantly hotter than the remainder of the core. The weakened graphite in the Station 20 to 30 region is associated with regions of known extensive "mid-range" corrosion where thermal capsule measurements have shown a maximum temperature of 1600 to 1700°C (Fig. 36).

Several special studies showed that (a) there was a correlation between the weakening of the center section and visible external corrosion, (b) elements believed to be in a region of steep radial temperature gradient did not differ significantly from the average element in strength, and (c) elements adjacent to and in locations similar to elements found broken in the core did not differ significantly from the average post-test element.

The azimuthal radial temperature symmetry for this reactor is supported not only by the thermal capsule temperature measurements previously reported but by the uniformity of the average strength properties of the elements adjacent to these thermal capsule detectors (Fig. 37).

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Fig. 35. Location of fuel elements in Kiwi-B-4E.

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FABRICATION OF GRAPHITE MATERIALS

Phoebus-1B Reactor Fuel Elements

Most of the U^{235} loaded fuel elements for the Phoebus-1B reactor are being fabricated at the UCNC Y-12 Plant. A few special lots of loaded fuel elements which will be used in experimental clusters in the reactor are being made at LASL. A 44-element lot containing 450 mg U/cm^3 has been extruded for use in the clusters which contain fuel elements having 0.110-in. diam instead of the regular 0.100-in. diam reamed holes. The purpose of the experiment is to note any problems which might arise in reactor operations due to the larger diameter holes in the fuel elements, since the larger holes will be used in the Phoebus-2 reactors.

A 45-element lot containing 504 mg U/cm^3 and a 45-element lot containing 492 mg U/cm^3 also were extruded for experimental clusters in the Phoebus-1B reactor. After NbC coating, one lot of fuel elements will be machined by electrical discharge techniques (Elox) in order to obtain perfectly flat surfaces without any NbC protrusions which might create gaps between elements. A better fit-up between adjacent fuel elements should minimize the presence of H_2 and the resulting corrosion. The second lot of fuel elements will be used in the tab-tip experiment. In this support scheme the present support block is eliminated and the fuel elements are supported through a tab located on one face of the element at the hot end. The flat surfaces of these elements also will be Elox machined after the NbC coating has been applied in order to achieve very flat surfaces for the full length of the fuel element.

A total of 263 fuel elements were extruded as six different lots in which the loadings ranged from 246 to 433 mg U/cm^3 . These elements were required for Phoebus-1B neutronic measurements in the PARKA assembly, which reproduces accurately the U loadings in the Phoebus-1B reactor.

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Phoebus-2 Zepo Fuel Elements

The U loadings for the balance of the Phoebus-2 Zepo fuel elements have been released and extrusion has been started. An additional 775 fuel elements covering ten U loadings, ranging from 187 to 352 mg U/cm³, will be extruded by September 10, 1965 for Zepo and 30 elements will be processed at the same time and in the same manner, including unloaded glued tips, for hot-gas testing. All of the stock will be extruded to have an as-graphitized hole diameter of 0.105 in. which will be reamed to the 0.110-in. diam of the Phoebus-2 design. The fuel element bores will be coated with NbC after machining.

The center elements in the Phoebus-2 Zepo clusters are made of unloaded graphite and some flexibility in adjusting the C content of these elements was desired. A total of 786 pieces of unloaded graphite rods, 0.370-in. diam by 52-in. long, were extruded and processed through all thermal cycles. The average C density of the pieces was 1.882 g/cm³. These rods can be inserted into the large hole in the center element.

Miscellaneous Graphite Components

A number of other graphite components are required to complete the reactor core and most of the material required has been delivered for final machining. A total of 445 unloaded center support elements, i.e., the center element within a cluster of fuel elements, were submitted for final machining. Thirty-three pieces of the same component were processed through the heating cycles in new fixtures so that the U contamination would be kept to zero. These particular pieces will be used in radiochemical analyses following the reactor test.

A total of 141 center elements were prepared containing 230 mg Ta/cm³ to be used as poison elements in the reactor. The Ta was added as TaC powder to the graphite mix and the elements were processed in the normal manner.

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The periphery of the reactor core has a transition zone, depending on the periphery design, in which unloaded graphite filler strips are required. The filler strips make the transition from the edge of the U loaded fuel elements to the pyrocarbon (PyC) tiles mounted on the inside of the cooled graphite slats. A total of 270 unloaded, solid hexagonal extrusions were prepared for machining into the required filler strip configuration.

The change in the periphery design of the Phoebus-1B reactor core, from the jagged to the circular geometry, resulted in a change in the design of the cooled graphite slat. In order to expedite the machining of these pieces, which contain either two or three cooling channels running the full 52-in. length of the slat, a new die was designed to extrude the shape with the cooling holes in place. The die was designed to produce an extrusion 1.25 in. by 0.93 in. containing either two or three holes in the center. Several hundred graphite pieces have been extruded thus far and are being processed through the thermal cycles prior to machining. The same die will produce solid, rectangular stock which will be used for the relatively large-size filler strips in the new periphery design.

The instrumentation included within the reactor core requires that a slot or hole be cut into the graphite components for the insertion of thermocouples, capsules, etc. In an attempt to ease this problem, special unloaded center elements, which normally possess only one large hole in the center of the element, have been produced with a small instrumentation hole at each corner of the element (7-hole) or an instrument hole at only two corners and on a diameter of the element (3-hole). The holes are closed at various levels, as desired, by solid plugs of extruded graphite which are glued in place. The holes are thus sealed so that there is no flow of H_2 gas through the instrumentation hole. A number of 7-hole elements have been extruded and are being prepared for plugging and thermal processing.

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GRAPHITE FUEL ELEMENT DEVELOPMENT

Graphite Gluing Experiments

Work has been continued on the evaluation of the glue joint which binds the unloaded graphite tip to the loaded portion of the fuel element. The decision to use a tab-tip instead of a support block in the Phoebus-1C reactor has resulted in recent gluing operations being performed on graphitized stock only. A greater flexibility in tab-tip design is provided by moving the glue stage to this point. The glue was standardized on a Varcum plus 50 parts per hundred (pph) graphite flour (-400) mesh. The glue curing cycle consisted of heating the glue joint, held together by a tie rod with a 3-lb spring, to 340°C over a period of 20 h. The high temperature processing of the glue joint, in most cases, was delayed until the fuel element had been machined and was ready for NbC coating. In the leaching furnace, the glued element is heated to 1650°C in a He atmosphere prior to introduction of the leaching gas and the glue "graphitized" in this manner. Permeability tests are made on all glued joints to evaluate the leak tightness of the joints.

The results thus far indicate that the joint rejection rate would be extremely low if a maximum leak rate of 0.5 liter/min were established as a fuel element specification. In general, 75% or more of the fuel elements tested in the cured condition (before NbC coating which tends to close pores and decrease leaks) had leak rates ranging from zero to 0.10 liter/min and most of the remaining 25% or less did not exceed 0.5 liter/min. Although there is a lack of data since the permeability test was not developed until late in Phoebus-1A production, the present glued joints are considered to be far superior to those on the Phoebus-1A fuel elements. Metallographic examination of many glued joints indicated that the joint thickness using Varcum plus graphite flour (-400 mesh) was between 0.001 and 0.002 in. as compared with 0.004-0.005 in. for the Great

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Lakes P-514 glue used in Phoebus-1A production. It is, in fact, very difficult to find the glue joint on the machined fuel elements.

The modulus of rupture, as derived in a thirds point flexure test, was determined for joints on Phoebus-2 Zepo fuel elements in which the element and unloaded tip were either in the baked or graphitized condition at the time of gluing. The results indicated higher flexure strengths for those elements glued in the baked condition, the average values being 2600 psi vs. 1770 psi for elements glued in the graphitized condition. Permeability tests indicated low leak rates with no significant difference being apparent between the two groups of fuel elements.

Although the program has produced a graphite glue, a joint design, and a process which yields a significantly better glued joint than that on the Phoebus-1A fuel elements, a few additional experiments are in process. Varcum resin plus 25 pph graphite flour (-400 mesh or finer) has shown unusual flexural strengths on a very limited number of test specimens and additional specimens have been prepared with the lower filler content in the glue. An increase in spring pressure holding the joint together during the glue curing operation has also revealed some interesting results. Development Lot 50 with a loading of 172 mg U/cm^3 was prepared for NbC coating development and hot-gas testing. Unloaded tips were glued on the 89 fuel elements with the standard Varcum glue, the only difference being a 10-lb spring load instead of a 3-lb load. Leak testing of the glued joints after curing revealed only three elements with leak rates of 0.005 liter/min. For the remaining 86 elements no leaks could be detected. In a similar experiment 15 fuel elements from Lot 54, containing 480 mg U/cm^3 , were glued in an identical fashion to the elements in Lot 50. Again, three joints had leak rates of 0.003 liter/min, and all other elements indicated zero leak rates. Additional elements have been processed with the higher spring pressure to confirm these results.

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High CTE Graphite

The characteristics of the Lot 1 graphite flour, prepared from special air blown coke by Union Carbide, were described in the preceding report (LA-3341-MS, p. 77). The coefficient of thermal expansion (CTE) of a 0.25 in. o.d. by 0.10 in. i.d. extrusion prepared from Lot 1 flour averaged 5.2×10^{-6} in./in./ $^{\circ}\text{C}$ over a temperature range from 25 to 1100°C . The CTE was found to vary only slightly as the C black (Thermax) content in the extrusion mix varied from 11 to 19 w/o.

Several shipments of Lot 2 of high CTE flour have been received from Union Carbide. Lot 2 is basically the same material as Lot 1 except that the primary flour so obtained will be subjected to several variations in subsequent processing operations. The primary flour from Lot 2 was mixed with 15 w/o Thermax and the binder content varied from 19 to 25 w/o. A binder content of 21 w/o resulted in "normal" extrusion pressures indicating that the binder requirement for Lots 1 and 2 are similar but well below the requirement for graphite flour used in fuel element production .

The additional material from Lot 2 flour received thus far has been subjected to the regular screen analysis for particle size distribution. The only difference from previous flours noted thus far is that the average size of the -325 fraction is larger (7μ) than that of other flours (3μ).

Fuel Elements for Coating Research

The graphitizing temperature currently being used in fuel element production is 2250°C and the fuel elements are at temperature for 4 h. Although the fuel beads should take this treatment, the low U tolerance of the NbC coating operation may require zero migration, diffusion, or presence of U at the coating surface. Two lots of 22 samples each, loaded to 480 mg U/cm^3 , were extruded to be processed in the normal manner except for the graphitizing temperature, which will be lowered to 1900°C . There

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should be no movement of U in the current beads at this temperature. One batch was extruded for the 0.100-in. diam final hole and the other to yield a final 0.110-in. diam. The elements will be evaluated in special leaching and NbC coating experiments.

Four additional lots of unloaded fuel elements were extruded with various amounts of wood flour. There were 26 extrusions in each lot and the wood flour content was 1.25, 2.50, 5.0, and 10.0 parts, respectively, of wood flour per 100 parts of graphite flour-Thermax. The binder content varied from 27 w/o for the low wood flour content to 30 w/o for the high flour level in order to obtain crack-free extrusions at the normal extrusion pressures. These elements will be used in the coating development program to evaluate the effect of matrix porosity on NbC adherence to the fuel element.

Approximately 350 fuel element extrusions were produced to be used eventually in NbC coating experiments. The U loadings were either 172 or 480 mg U/cm³ and the same elements will supply data on gluing experiments during the normal processing operations. Approximately 200 unloaded fuel elements also were supplied for the NbC coating development program.

Hydrostatically Pressed Graphite

Work has been continued on the development of an isotropic, uniformly porous graphite by hydrostatic pressing techniques. Such a graphite may have an application as a support block or tab tip material if it is strong and if an adherent NbC coating can be applied to it. The wood flour addition for most of the pressing was arbitrarily selected at 4 parts of wood flour per 100 parts of dry C and the Varcum binder content ranged from 8 to 26 w/o. The graphite flour used in the mix was also varied. The standard thermal cycles used for fuel elements was employed with the exception of the graphitizing temperature, which was raised to 2500°C.

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Some of the pressings bonded with 8 and 10 w/o Varcum were too weak to be machined after graphitizing. As a first evaluation, the graphitized blocks are radiographed and compression samples machined from two directions in the block. The preliminary data from the first blocks processed - before most of the difficulties had been solved - indicated compressive strengths ranging from 1000 to 5500 psi. The material indeed appears to be isotropic in that there is little difference between strength levels in the longitudinal and transverse directions. It also appears that the wood flour and binder contents exert a strong influence on strength and, to some extent, on the density.

Experimental Graphite Manufacture

Preliminary results indicate that curing in air, instead of He or H₂, significantly increases both the density and the strength of a molded graphite made from a graphite flour-Thermax-furfuryl alcohol formulation.

Additions of furfuryl alcohol to a pitch-bonded graphite flour-Thermax mixture, to inhibit slumping during baking, have resulted in relatively low densities in the graphitized bodies. Densities are further reduced by lubricating additions of paraffin or methyl cellulose, but increase slowly with an increasing ratio of furfuryl alcohol to coal-tar pitch in the mixed binder.

Solid Stock for Tab Tips

The tab tip design of support system, which eliminates the present support block, will require unloaded graphite which can be machined into the fuel element cross-section plus a tab protruding from one of the six flat surfaces. In addition to the commercial graphites being evaluated for machinability, strength, and coatability for this application, solid extruded stock is being prepared by LASL techniques for similar evaluation. The green extrusions are approximately 1.1-in.

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diam and the extrusion mix is composed of the standard graphite flour-thermax composition plus 1.25 parts wood flour to 100 parts of dry C ingredients. The wood flour was added to promote soundness of the solid stock as well as to assist in the NbC coating adherence problem.

The relatively large diameter complicated the extrusion operation because of the large mass of material flowing through the die. In such an extrusion, it is easy to have the center of the extrusion flowing faster than the edge resulting in shear forces and cracked extrusions. A three-legged spider containing a stub pin was used in several experiments in an attempt to regulate the flow of material. The cured extrusion exhibited longitudinal cracks which corresponded to the position of the spider legs, indicating that not enough pressure was available to knit the flow lines. An extrusion was then made without the spider in a larger extrusion press, resulting in a larger reduction ratio during the extrusion. The extrusion rate was very high (40 ft/min) but the graphitized stock looked sound and appeared to be free of cracks and radiographic results provided confirmation. The density of the graphitized stock was 1.833 g/cm³.

Carbide Loaded Extrusions

The presence of refractory carbides in the graphite matrix might possibly inhibit the corrosion observed in the hot H₂ tests. A few experiments were undertaken to determine the problems in extruding and processing graphite containing various amounts of refractory carbides. Small size extrusions, 0.25 in. o.d. by 0.10 in. i.d., were made in graphite loaded with 0.4, 0.8, 1.2, and 2.0 g/cm³, respectively, of TiC or ZrC powder. The loading is based on metal (Ti or Zr) weight. Extrusions of ZrC loaded to the 4.0 g/cm³ level and of pure TiC and ZrC bonded only with the Varcum resin were also produced. Similar experiments were performed with Ta, added either as the metal or as TaC, and the loading in graphite ranged up to 8.0 g Ta/cm³. All the material could be

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extruded, although it must be noted that this is a very simple die and quite different from the complex die used to extrude fuel elements. The materials were cured and the batches then split, half being carried through graphitization in the fuel element furnaces and half being used for various evaluation experiments.

An attempt was made to produce a loaded fuel element containing ZrC as the refractory carbide. Two extrusion lots were extruded containing 480 mg U/cm³ and 0.5 and 1.0 g Zr/cm³, respectively. Similar lots, without the U, were extruded at the same time. The extrusion was difficult and the Varcum resin level had to be increased significantly. After the 850°C baking operation, the elements had a loose smudge on the surfaces, possibly due to some reaction of ZrC in the relatively poor vacuum. Machining was also much more difficult due to the presence of the carbides and only the unloaded lots (no U) could be machined.

Binder Resin

All planned laboratory evaluation tests on Varcum 8251 resin have been completed. The relationship of properties to the amount of furfuryl alcohol added at the last stage of resin manufacture appears to be roughly linear. The low heating rate DTA studies of the resin produced no information other than indicating the difficulties inherent in relating DTA data to process conditions. Recent TGA measurements indicate that some change must be made in the test equipment to approach actual graphite processing conditions.

Experimental extrusions 0.25 in. o.d. by 0.10 in. i.d. were made with a phenol-formaldehyde base resin and furfuryl alcohol base resins of different viscosities. All of the graphite batches were bonded with 27 w/o resin and hand mixed, since the more viscous resins could not be used in the standard blender. The phenol-formaldehyde bonded extrusion possessed the lowest density (1.835 g/cm³) but the highest modulus of rupture (6600 psi). The various furfuryl alcohol bonded extrusions

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indicated higher densities (1.85-1.89 g/cm³) but lower moduli of rupture, ranging from 5387 to 6187 psi. For comparison, an extruded piece of the same size made with production Varcum resin had a density of 1.865 g/cm³ and a modulus of rupture of 5850 psi.

Brazing of Graphite

A development program to parallel that of gluing unloaded graphite tips onto the hot end of fuel elements involved metal brazing of the two members at high temperature (LA-2241-MS, p. 79). A butt joint was selected in place of the mortise and tenon type joint used with the glue. Foils of the metals under examination, which are strong carbide formers, were used as the braze material. The braze joint was held under a nominal pressure while the joint was heated rapidly in a h.f. induction coil.

The encouraging preliminary results on brazing with Mo led to additional experiments with unloaded graphite using Mo foil 0.002-in. thick. The foil was blanked into a hexagonal shape to match the fuel element but without any holes. Fifteen samples were brazed and all possessed zero leak rate. The room-temperature flexure strengths ranged from 2600 to 4600 psi with an average for all tests of 3600 psi. This is a significant improvement over the strength of glued joints.

Specimens were prepared in which the unloaded graphite tip was brazed to a section of loaded fuel element with the 0.002-in. thick Mo foil. The samples represented a variety of conditions, including leached and unleached loaded material and solid or drilled Mo foils. In practically all cases, the permeability test indicated zero leakage at the brazed joint. The room-temperature flexure strengths on unleached loaded specimens ranged from 3200 to 3800 psi with failure occurring in the braze joint. Specimens in which the loaded element was leached prior to brazing had flexure strengths from 2100 to 2900 psi, again with all failures being in the joint. These results indicated that brazed

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joints probably were better than glued joints at room temperature. However, since the joint must function at high temperature, it was necessary to obtain data on the strength of the joint at elevated temperature. This evaluation could not be done with a flexure test and it was necessary to adopt a straight tensile test. A number of problems associated with graphite grips glued to the test specimen resulted in some uncertainties in the data.

The room-temperature tensile strength of brazed joints ranged from 1500 to 2100 psi and appeared to be independent of whether the loaded portion of the joint had been leached or was in the as-machined condition. These specimens for the most part also failed in the joints.

The results from the high-temperature tension tests are quite erratic but indicate that potential problems are low melting carbide-C eutectics, heating rates, and temperatures. Most of the tests were run at an uncorrected temperature of 2400°C in a dead-weight testing apparatus and the samples were heated in a h.f. induction coil. The unleached joints did not exceed 300 psi tensile strength at temperature, the joints leached after brazing ranged from 90 to 600 psi, and the joints leached prior to brazing produced one joint which did not break at the testing machine capacity (762 psi) even at 3000°C . This sample, tested in flexure after the high-temperature tensile test, indicated a flexure strength of 2100 psi. The high-temperature test results are an indication of possible low strength at reactor operating conditions but there were so many problems associated with the test itself that any conclusion is premature.

The possibility of a liquid eutectic being present when pure Mo is used as the braze metal has suggested the investigation of braze alloys of Mo, Nb, Ta which would result in higher temperature carbide-C eutectics. This program will be started in the immediate future.

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A few samples in the leached condition were brazed with the 0.002-in. thick Mo foil and then coated with NbC. The coated specimens were tested at 2450°C in H₂ without any evidence of corrosion or mechanical failure at the joint. As the brazing development program continues, full-length fuel elements with brazed tips will be included for NbC coating and hot-gas testing evaluation.

Improving the Structure of Pyrographite

Simultaneous application of compression and torsion at high temperatures has converted a continuously-nucleated pyrolytic graphite, having a well-developed fine cone structure, into a highly-ordered graphite having essentially the interlayer spacing of an ideal single crystal and a very high degree of order in the orientation of layer planes. Periodic rotational disorientations, however, at intervals of about 500 to 1000 Å, have not so far been eliminated, and means of producing large single crystals from this pyrographite have not yet been developed.

X-Ray Studies on Graphite

LASL experimental graphites produced from a graphite flour-Thermax-furfuryl alcohol mix, have been found to increase in average interlamellar spacing and decrease in average oriented-layer thickness during graphitization. This is attributed to graphitization of binder coke, forming finer and less well-ordered crystallites than those initially present in the graphite flour, which is little affected by the graphitizing treatment.

Pyrocarbon layers deposited on Pt discs have been found to contain a highly-crystalline graphite component formed near the Pt substrate and in a nearly perfect epitaxial relation to it.

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Tensile Behavior of Graphite

Tensile stress in a commercial reactor-grade graphite held at constant strain has been found to decrease linearly with the logarithm of time in tests at 2200 to 2600°C. Apparent activation energies for the relaxation process decrease with increasing temperature in this range, suggesting that more than one relaxation mechanism is active.

Preliminary experiments in which steady-state creep of graphite is interrupted by a rest period under zero load indicate that the rate-law $\dot{\epsilon} = At^{-n}$ is observed during periods of continuous creep, but that the constants in the equation are disturbed by the rest period.

Microscopy of Graphite

Optical Microscopy

A technique of ion-bombardment in a reactive gas, e.g., H₂, has been devised for etching of graphite for examination by optical and electron microscopy. It has been found to develop cleaner, sharper, and more revealing microstructures than does any other etching method so far used at LASL.

Size distributions of particulate raw materials are now being determined optically by a procedure which involves dispersing the particles in the Micromerograph, catching a sample of them on double-coated Scotch tape, and photographing the sample at 250X under polarized vertical illumination.

Electron Microscopy

A JEM-7 electron microscope has been installed, adjusted, and demonstrated to produce the guaranteed resolution of 4.5 Å. Techniques have been developed for replica and direct transmission microscopy of graphite, and structural examination has begun of both natural and manufactured graphites.

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Fuel Element Coating Development

Extended leaching experiments have been conducted with bead-loaded elements in attempts to remove all of the contained U in preparation for coating experiments. Two somewhat unexpected observations were made. First, it is extremely difficult to leach all of the U from bead-loaded elements even after the elements have been heated to high temperatures. Second, low concentrations of residual U promote the characteristic non-adherence of NbC coatings deposited on fueled graphite.

In the experiments, fuel elements were first heated at 2450°C in an attempt to destroy the PyC coating on the beads. After leaching at 2100°C for 150 h, ~95% of the contained U had been removed and the loss rate (per element) was less than 100 mg U/h at 2100°C. However, coatings deposited (on two of the elements) at 1900°C exhibited the nonadherence characteristic of U-loaded graphite in contrast to very adherent coatings on unloaded graphite in the same coating batch.

Elements from the leaching experiments described above were leached at temperatures between 2100 and 2450°C for an additional 100 h and then coated at 1900°C. Once again, the coatings exhibited the non-adherence characteristic of loaded graphite, despite the fact that the residual U in the element must have been low in quantity. Examination of the coat-matrix interface by α counting revealed the presence of U in the coating next to the interface. This "concentration" effect is characteristic of coatings on loaded graphite.

Coated Particle Research and Development

Introduction

Laboratory-scale work on the deposition of PyC coatings on fuel particles in 1-in. diam coaters and evaluation of the resulting coated particles were continued. This is being done within the general framework of coated particles of current and potential interest for use in fabrication of fuel elements. The basic requirement is for PyC-coated particles

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with adequately high U content and good thermal stability at 2300°C and higher temperatures.

"Upgrading" of General Atomic UC₂ Particles

Attempts were made to "upgrade" GA UC₂ particles which have a complete proeutectic C shell, to determine if samples of coated particles could be prepared from them in which all of the particles would survive heating at 2500°C for 30 min. One procedure was to heat samples in air at 400°C for 6½ h to disrupt those UC₂ particles with proeutectic C shells permeable to O₂, leach the oxidized samples in 5M HNO₃ on a steam plate several times until the supernatant liquid was colorless, and separate the surviving UC₂ particles from the proeutectic C debris with 1,1,2,2-tetrabromoethane. Yields were about 50%. One-gram samples of these "upgraded" cores were coated under conditions to give the best, i.e., migration resistant, nominal 40-μ coatings which could be deposited from CH₄ at 1200 and 1300°C. The resulting coated particles showed no migration at 2300°C in 3 h, as would be expected. However, about 50% U was exposed in 30 min at 2500°C, as determined by leaching and U analysis. These results were similar to those obtained on particles with comparable coatings on untreated GA cores from the same batch.

The other method of "upgrading" was to heat a selected batch of particles with a nominal 25-μ coating on the same untreated GA cores for 30 min at 2500°C. The particles were then leached and elutriated, and the surviving particles were tested again at 2500°C for 30 min. Micro-radiography indicated a very pronounced improvement in the survival rate after the second heating.

Thermal Treatment of Coated Particles

WANL has reported informally on experiments designed to improve the resistance of PyC-coated UC₂ particles to migration at 2500°C by heating at or slightly above the melting point of UC₂-C for a short

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time, followed by soaking at a high temperature below the melting point. This treatment was applied at IASL to several samples of commercial particles and the results were evaluated by leaching with HNO_3 and analyzing for U.

Duplicate samples were heated at 2450°C for 5 min, cooled quickly to 2200°C , held there for 1 h, and then tested at 2500°C for 30 min. Microradiographs showed no indication of increased resistance to migration at 2500°C . The leach results confirmed this, as shown by the following data:

<u>Sample</u>	<u>Treatment before heating 30 min at 2500°C</u>	<u>% of Total U leached</u>
3M-EB-8.00 ⁽¹⁾	None (control)	101
	See text	100
GA-E-LY-1 ⁽²⁾	None (control)	87
	See text	87

(1) Crossblend of 3M enriched beads with outer high-temperature coating.

(2) First shipment of GA enriched beads on Purchase Order LY-15100

In a second set of experiments, the same treatment was used except that the initial heating was at 2400°C for 5 min. The particles were microradiographed before and after the final 2500°C test. Following the 2200°C soaking the GA-E-LY-1 particles showed essentially no migration and the 3M-EB-8.00 particles exhibited some migration but no failure. Following the 2500°C treatment, the GA particles were mostly destroyed but showed a few survivors and the 3M particles were completely destroyed. Quantitative HNO_3 leaching following the 2500°C treatment showed 91% of the total U removed from the GA particles and 101% from the 3M particles.

PyC Coatings from Acetylene at Low Temperatures

As reported previously (IA-3341-MS, p. 85) a coating deposited at 1200°C from 2½% C_2H_2 in He had good resistance to migration at 2300°C even

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though the coating density was only 1.68 g/cm^3 . (This was contrary to extensive experience with coatings deposited from CH_4 at 1200 to 1400°C , which indicated that both high density and high preferred orientation are required for good resistance to migration at 2300°C). A coating was deposited from C_2H_2 under identical conditions on GA UC_2 particles with a complete proeutectic C shell, to give a material in which the coating was isolated from the UC_2 . The density of the as-deposited coating was 1.73 g/cm^3 . The density of the coating removed from the particles after heating at 2300°C for 4 h was 1.93 g/cm^3 . It appears likely that the good resistance to migration at 2300°C was due to properties of the coating after reorganization under stress caused by expansion of the core. This result is consistent with effects observed at BMI when coated particles were subjected to stress by annealing in He at 1650°C and 10,000 psi.

NONDESTRUCTIVE TESTING

Production Inspection

Fuel Elements and Support Blocks

During the current quarter, NDT inspection of PARKA elements was completed. The inspection consisted of β probing the bores and γ scanning the elements to determine the U content.

Phoebus-2 Zepo elements were inspected in the machined and leached stages by γ -count methods for U content. The first coated elements were received toward the end of the quarter.

The support block production for Phoebus-1B has been in progress with NDT inspections being performed on the stock material. The radiographic observations revealed high-density material in the as-received pressings. After heat treatment, radiography indicated that some of the high-density material was still present.

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Several preproduction Phoebus-1B elements have been received and inspected. Standards for Phoebus-1B production γ counting have been obtained.

A number of fuel elements with very low loads ($< 5 \text{ mg U/cm}^3$) have been inspected. Since no standards were available, the loadings of these elements were obtained from an extrapolation of the present calibration curve. Confirmation of several of the reported values will be attempted by chemical analysis.

An investigation of the discrepancy between γ counting and chemistry determinations of U loading in coated fuel elements is being continued. Four coated samples for comparison have been obtained and are in process. The cause of the discrepancy has not yet been found.

Coat Thickness Measurements

A complete set of calibration standards for holes in the range from 0.094- to 0.114-in. diam for loaded and unloaded material has been prepared. These standards are for NbC coatings only. An additional standard has been prepared for TiC coatings.

Inspections of coated, center support elements, and support blocks for Phoebus-1B have begun. The inspection program for Phoebus-2 Zepo fuel elements has been initiated. Routine inspection of hot-gas-test elements and coating-development elements has continued.

Fuel Element Bore Replication

The first visual replica scanner has been placed in operation for retrieval of fuel element replication data. A second of modified design is in the process of fabrication. The scanner facilitates the visual inspection and photography of 52-in. long bore replicas using transmitted light. A table provides replica motion in two directions at right angles in the horizontal plane. In addition, replicas may be rotated around their own

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axes providing 360° inspection of the replica surface. System optics result in an 18X magnification of the surface detail.

Research and Development

High and Normal CTE Elements

Nondestructive testing was performed on fuel elements made from high-CTE graphite. They had been specially fabricated to bring the CTE of the graphite matrix and the NbC coating more closely together. These elements, together with the normal CTE elements coated in the same batch, were given the standard nondestructive testing inspections. Few data were obtained after the hot-gas test because most of the high-CTE elements broke. The data obtained before the hot-gas test were reviewed to determine: (a) any unusual physical characteristics which might have caused the high rate of breakage observed during hot-gas test, and (b) any significant differences between the high- and normal-CTE elements which would indicate improvement in the coating.

No important indications were found which would point to a cause of breakage during the hot-gas test. The only significant physical difference between high- and normal-CTE elements was a higher electrical resistance of the former. Four typical, loaded, high-CTE elements had an average electrical resistance of 1.70 mΩ/in. for comparable normal-CTE elements.

Significant improvement in the coating of the high-CTE elements was shown by replication. The high-CTE elements had fewer and smaller cracks, but they were more difficult to machine.

Bore Replicas

Results of preliminary experiments indicate that bore replicas, free of air bubbles, can be successfully produced utilizing the vacuum-forming technique.

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Metallography and Electron Microscopy

Cathodic vacuum etching experiments continued for the development of an etch that defines graphite flake structure. Ar gas was used by varying the electric potential and etching time, but it always produced pitting and extraction. Ne and Kr, separately, with and without r.f. excitation were also utilized. It was determined that the gas of higher atomic weight, i.e., Kr, produced less pitting than the lighter gas. Based on these observations Xe, having an even higher atomic weight, was selected. A reproducible etch technique was then perfected. Typical structures were obtained comparable to the quality given by the BMI-Northwest etch technique.

During the course of the experiments it was noted that gas bleeder pressure, required to produce a glow discharge, varied from 20 μ with Ne to 2 μ with Xe. The addition of r.f. excitation further reduced the gas pressures slightly, and permitted operation at a lower potential while increasing the discharge beam diameter on the specimen with no adverse effects.

A chemical etchant has been developed that is suitable for both optical and electron metallographic studies of NbC coatings. It facilitates the study of coating microstructures on graphite fuel elements. The KOH-H₂O₂ etchant reveals NbC grain boundaries, grain size, and a secondary phase in the NbC matrix. Examples of coatings etched by this method are shown in Fig. 38. The technique provides a means for studying microstructural changes occurring in the coatings as related to variations in coating chemistry.

Thermal Conductivity Study of NbC Coating Adherence

The thermal scanning technique has been refined and is becoming a reality. The arrangement of the apparatus is shown in Fig. 39. A Cassegrainian telescope has been constructed as a receiver in the radiometer

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Fig. 38. Etched NbC coatings.

Fig. 39. Schematic diagram of thermal scanning apparatus.

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head. The primary of the telescope is a 6-in. diam, Schmidt-type television mirror with a 1.6-in. diam hole through the center; the secondary is an Al-coated positive lens with a diameter of 1.5 in. Thermal radiation that passes through this telescope is "chopped" by a 90-cps motor-driven chopper. The radiation is then incident on a detector, which can be a bolometer or a PbS or PbSe cell. The resulting signal is preamplified and then passed to an amplifier and recorder.

The specimen is heated by a system composed of a 1000-W tungsten lamp, reflector, and a converging lens of large diameter and long focal length. Relative motion between the radiometer and target is provided by an X-Z scanner which is under construction.

A new technique for measuring relative thermal conductivity of NbC coatings is being investigated. A commercially available, thermally-sensitive phosphor is attached to a specimen. This specimen is heated to about 80°C (the phosphor loses its luminescent properties if heated above this temperature) and cooled. During the cooling process, bonded areas are dim, since heat transfer between the graphite and NbC is better for bonded than for nonbonded areas. The luminescence of the phosphor is greater at lower temperatures. This technique promises to provide a "thermal picture" of a given surface, showing bonded and nonbonded areas. The phosphor is attached to a paper substrate which is affixed to the specimen as an ordinary decal. The decal can be dissolved with acetone after use.

Instrumentation Development

Eddy-Current Inspection

An investigation has been started into the feasibility of using a three-phase eddy-current system for fuel element inspection. Work has been done to develop the generating system and to build a prototype external inspection coil assembly. It uses three coils in which the ac is shifted $\pm 120^\circ$ with respect to the reference signal phase. This causes a rotating field to be set up in the center of the coil system. The field in turn

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causes eddy currents to be introduced in the graphite matrix. The configuration of the coils is such that the eddy currents flow along the length of the fuel element. Pickup coils are inserted into the outer bores of the element; thus, any defect which distorts the current distribution causes the signal on the pickup coil to change. Defects which are in the transverse plane cause the maximum distortion of the eddy currents whereas defects in the longitudinal plane cause little or no distortion. Hence, the system should be primarily sensitive to transverse defects.

The experiments performed with the prototype coil and pickup system show this to be essentially true. Longitudinal defects with a finite width cause the eddy-current density to change, which in turn causes a change of the signal on the pickup coil. By proper choice of the associated electronics, the sensitivity of the system is equal to that of the external eddy-current inspection system presently used. The latter system uses coils which are roughly circular and are almost equally sensitive to both transverse and longitudinal defects.

The work done so far shows the three-phase system to be feasible. However, considerable development work is required on both the electrical and mechanical portions to make this system operational.

Coordination with other Installations

Coordination with Oak Ridge

Two problems have been encountered in the Oak Ridge Y-12 eddy-current inspection of Phoebus-1B fuel elements. The inspection is performed with the aid of automatic equipment which punches out the position of eddy-current indications on cards. After the element is inspected, the cards are fed into a computer which evaluates the indications and categorizes (or grades) the elements according to the Phoebus-1B specifications. It was found that the computer program was incorrectly written and that elements manufactured and tested by Oak Ridge for the Phoebus-1A and -1B reactors were improperly categorized.

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Oak Ridge has consequently been requested to correct the program and to rerun all Phoebus-1B fuel element eddy-current inspection cards with the exception of Category 1 elements. The results of this reevaluation will be forwarded to LASL for action. Furthermore, the automatic equipment which senses an indication and punches the computer card, misses the second indication when two internal indications are separated by 1/2 in. or less. It is not known at the present time what is the cause of this malfunction. The missing of indications could account for an erroneous upgrading of an element.

A program for correlating nondestructive test data between Oak Ridge and LASL for Phoebus-1B elements is being formulated. This program will provide for eddy-current and γ -count data on elements in the leached state and for γ -count and β -backscatter data on elements in the coated state. Additional tests, such as potential drop, D_xT, and replication will also be performed on some or all of the coated elements.

Mutual Problems with Y-12 and WAFF

In order to establish a common basis for γ -count load measurements, LASL, WAFF, and Oak Ridge are cooperating in an exchange of data on two leached fuel elements. They will be γ -scanned and analyzed for U content by chemical methods at each of the three organizations. The data will then be used to establish any differences that might exist between the various γ -counting and analytical methods. Consideration of a similar step for coated fuel elements will be made after this study has been completed.

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V. MATERIALS DEVELOPMENT

CERMET DEVELOPMENT PROGRAM

Alloy Development

The program to investigate the mechanical properties of W-Mo-Re alloys has been started and test specimens are being prepared. Tensile, compression and flexure specimens are being prepared from wrought sheet and, for comparison, from pressings prepared by conventional powder metallurgy techniques. The wrought alloys under investigation contain either 7 or 12 at/o Re added to 80-20, 70-30, 60-40, and 50-50 w/o W-Mo compositions.

The sequence of operations for preparing the wrought material from which the test specimens were taken was as follows:

1. Powder blends were hydrostatically pressed into slugs at 45,000 psi.
2. The pressed slugs were sintered in H_2 at $1700^{\circ}C$ for 3 h after which they were sintered an additional 1.5 h in H_2 at $2700^{\circ}C$.
3. The slugs were then cut in half and Dynapak forged at $1750^{\circ}C$ into plates suitable for rolling.
4. After surface conditioning, the plates were rolled at $1700^{\circ}C$ to ~ 0.065 -in. thick.
5. The rolled sheet was grit blasted and conditioned at $1400^{\circ}C$ for 72 h in H_2 , after which the sheet was flattened with W weights at $1400^{\circ}C$ in H_2 for 2 h.

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6. Tensile specimens were Eloxed from the sheet and finally flattened with W weights at 1600°C for 1 h in H_2 .

The tensile specimens are currently being ground to remove rolled surface irregularities, after which they will be stress relieved at 1400°C in H_2 for 1 h prior to testing.

The W-Mo alloys to be investigated by powder metallurgy techniques include the 80-20, 70-30, 60-40, and 50-50 a/o compositions with the addition of 0, 7.0, 12.0, or 17.0 a/o Re. However, before fabricating test specimens it was necessary to determine the optimum sintering conditions for these alloys. The results indicate that the Kirkendall effect is more dependent upon particle size than on sintering temperature. It was concluded that something close to the optimum particle size was used in this investigation on a 50-50 a/o W-Mo composite containing 17 a/o Re, since the densities of practically all specimens ranged from 92 to 93% of theoretical after sintering in H_2 for 1.5 h at 2350°C . If one or more of the powders used contained particles of $20\text{-}\mu$ size or larger, it would be extremely difficult for the high-temperature sinter to overcome the Kirkendall effect.

Blends of these alloys have been made and hydrostatically pressed into blanks suitable for fabrication of tensile, compression, and flexure specimens. Preliminary sintering results on specimens sintered in H_2 for 3, 6, and 24 h at 1700°C followed by 1.5 h in H_2 at 2350°C also suggested that the particle sizes used were correct since sintered densities at 95% of theoretical were obtained.

A batch of W-25 w/o Re alloy powder was received from Oak Ridge and samples have been submitted for chemical and powder analysis. A program has been initiated to investigate the pressing and sintering characteristics of this alloy powder with and without Mo additions.

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High-Temperature Testing of UO₂ Cermets

Tests run at 2600°C in flowing H₂ tend to confirm the data reported previously which indicated that Y₂O₃ in a cermet minimized the loss of UO₂. The cermets contained 4 v/o Y₂O₃ and its addition to the UO₂ fuel was found to be more effective than if added to the metal matrix material. It has been possible to extend the 30-min cycle test (at temperature for 30 min, cool, and weigh) to 9.5 h or 19 cycles and still have a total UO₂ loss of only 1.8%. A few experiments have indicated that no additional benefits were obtained if the Y₂O₃ content was increased from 4 v/o to as high as 20 v/o.

There has been some indication that cooling the test specimen in vacuum after the 2600°C test in H₂ has a deleterious effect on the material. Since this condition would be similar to the operation of a fuel element in space, experiments are being undertaken to investigate the effects of such a cooldown condition on the integrity of fueled cermets.

Metallographic examination of W-coated specimens after the 2600°C test for various periods of time has revealed isolated areas only of recrystallization of the W coat. The W structure remained essentially columnar in all cases, although there was considerable broadening and evidence of an unidentified phase in the grain boundaries after numerous 5-min cycle tests.

Vapor Phase Coating

Several W tubes were prepared by depositing W from WF₆ decomposition upon mandrels of different materials. Two tubes were fabricated by coating Mo tubes and then dissolving the Mo away in HNO₃ solution; one was 6 in. long with a 0.005-in. thick wall and the other was 10 in. long with a 0.010-in. thick wall. Graphite and Cu were also used as mandrel material. Attempts to W coat quartz tubes were unsatisfactory because of the quartz cracking upon cooldown due to the difference in thermal expansions.

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Several experimental runs were made to develop a technique for coating fuel beads (PyC-coated UC₂ particles) with a 0.0005-in. thick layer of W. Prototype runs were made with Al₂O₃ particles as a substitute for the beads. The fuel particles were coated successfully at 550°C and 250 torr.

Attempts to coat beads or Al₂O₃ particles by the H₂ reduction of MoCl₅ were not too successful; the particle temperatures ranged from 600 to 800°C and coating (reactor) pressures from 60 to 100 torr. The best coat appeared at 800°C and 100 torr and a H₂/MoCl₅ ratio of 10/1, but this coat was of poor quality since it was not smooth in appearance and varied in thickness. A supply of MoF₆ has now become available and preliminary runs at 600 and 800°C indicate that coating with this material will be much more successful.

METAL SUPPORT SYSTEM

Phoebus-2 Tie Tubes

The dimensions of the inner and outer tubes of Inconel 718 for the Phoebus-2 tie-tube assembly were changed to obtain a better gas flow. The order for tubing to meet a rigid LASL specification has been placed with a vendor, the earliest delivery date being December 1, 1965. The tooling for the ribbed support pieces, transition section, and end cap must be changed to accommodate the revised tie-tube design.

The original tube stand-off exhibited a pressure drop (ΔP) that was higher than desired, although some of the effect may have been due to the presence of cutting burrs on the pieces. However, several different stand-off designs have been prepared and submitted for ΔP evaluation.

The tie-tube design originally called for brazes to join the outer tube to the transition section and the end cap to the transition section. It now appears that both joints may be electron-beam or W inert-gas welded

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to provide better joints and easier assembly operations. Experimental welds of both types are currently under investigation. In conjunction with the end cap weld, welds were made to join heat-treated to non-heat-treated Inconel 718 sheets. There was no evidence of weld cracking in any of the test pieces. The mechanical properties of similar joints also are being investigated.

Several prototypes of tie-tube brazed joints are being made to examine the brazing procedures contemplated for tie-tube assembly. Brazes have been made in an Ar atmosphere containing various amounts of H₂O vapor and O₂. The appearance of the tube and its brazed joints is significantly different if the Ar atmosphere contains less than 5 ppm of H₂O vapor; the brazes and the tubes are very bright and are comparable to those brazes made in a vacuum. Above 5 ppm the tubing and the brazed joints are discolored and considered unsatisfactory. The IASL brazing and heat-treating furnace should be capable of operating under vacuum or in a dry inert atmosphere.

Metallographic examination of brazed joints previously inspected by NDT techniques indicate excellent agreement between metallographic and radiographic results but less satisfactory agreement with ultrasonic data. All of the brazes and welds in the tie-tube assembly will be radiographed, with some ultrasonic inspection in selected areas.

REACTOR CONTROL MATERIALS

Phoebus-2 Control Plates

Cu-B₄C Mixtures

It was noted in the preceding report (LA-3341-MS, p. 110) that Cu-50 w/o B₄C is essentially the equivalent of the Al-20 w/o B¹⁰ control plates used in the Kiwi and Phoebus-1 reactors. It has since been noted that Cu-40 v/o B₄C (16 w/o) is not very different neutronically from

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Cu-50 v/o B_4C although there is a noticeable difference in fabrication behavior. Consequently, the control plates for the Phoebus-2 reactor will have a composition of Cu-16 w/o B_4C (40 v/o). A firm design has been established and tooling to form the 0.100-in. thick strips to the desired contour is being developed.

Spheroidization of B_4C Particles

Most of the development work during the current period was concerned with the spheroidization of the B_4C powder. The commercial powder has a very angular shape which is not too desirable for powder metallurgy operations. The large volume (40%) of B_4C in Cu also indicated that relatively large particles should be used in order to obtain a Cu matrix possessing ductility and having the capability of being formed in subsequent operations. The plasma gun available for spheroidizing worked well on the smaller size particles but only rounded the sharp corners on the larger particles.

The resistance heated, graphite-tube drop tower (LA-3341-MS, p. 111) proved very satisfactory in spheroidizing B_4C particles in all sizes. Metallographic, x-ray, and chemical analyses, however, indicated that the structure of the high-purity starting powder had been degraded during the spheroidizing operation. The particles revealed internal porosity and, of greater importance, the C content was increased by a significant amount. These runs were made at an optical temperature of $2500^{\circ}C$ or a true temperature in the neighborhood of $2650^{\circ}C$. A number of spheroidizing runs were made at optical temperatures ranging from 2200 to $2550^{\circ}C$, in $50^{\circ}C$ increments, to determine the spheroidizing range. Partial spheroidization occurred at $2350-2400^{\circ}C$ and complete spheroidization took place at $2450-2500^{\circ}C$. Chemical analyses, however, indicated C pickup concurrent with the start of spheroidization. A graphite heating tube was coated with NbC in an attempt to minimize the C pickup. At the spheroidizing temperature the NbC coating also encountered a liquid phase and the coating ran down the tube and did not provide any protection.

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At the same time that the graphite drop-tower investigation was under way, an induction-heated Ar plasma device for B_4C spheroidization was under development. This device was free of graphite components and preliminary work indicated that partial or complete spheroidization could occur without affecting the purity of the starting material. After considerable effort, it now appears that up to 15 lb of B_4C powder can be spheroidized per day and it is anticipated that all of the B_4C powder for the control plate program will be processed in this manner.

Production of Plates and Strip

Blends of the various B_4C particles with Cu powder have been prepared and hot-pressed in graphite dies into 2 x 2-in. or 5 x 5-in. plates 0.45-in. thick to be used for a subsequent rolling development program. The large hot presses with the capability of producing hot-pressed plates of much larger size are installed and now being checked out. Pressings from these units should become available during the next report period.

Some problem areas have appeared in rolling the Cu- B_4C pressed plates into strip 0.100-in. thick, the thickness of the Phoebus-2 control plates, and a development program was undertaken to minimize the difficulties. The most serious problem was edge cracking of the pressing during initial breakdown rolling. The reduction in B_4C loading from 50 to 40 v/o should help immediately. Plates rolled at an earlier date were canned in Cu, rolled at 600°C to 0.150-in. thickness, and then rolled bare at 300°C to 0.100-in. thickness. In an attempt to obtain better flow of the Cu during rolling, plates of Cu-50 v/o B_4C were rolled at 700 and 800°C to an intermediate thickness and then to 0.10-in. thickness at 400°C. The hot-pressed plates were either bare or Cu plated, and the metal can to prevent edge cracking was either Cu or mild steel. The Cu can was deemed unsatisfactory because it was very difficult to remove the can without obtaining a rough surface on the strip. This had not been a problem when the rolling was performed at 600°C. Bonding did not occur with the mild

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steel can and the surface finish of the plates was improved significantly. In general, the surface finish of plates rolled at 700°C was better than those rolled at 800°C. Pressings which were not Cu plated before rolling showed a certain amount of surface checking or cracking and metallographic examination indicated that the cause was B₄C particle breakthrough to the surface.

The mild steel can worked well on the 2 x 2 in. pressing but new problems were encountered when the 5 x 5 in. plate was rolled. The cans split at the welds if the can thickness was less than 0.080 in. but a more serious problem was the difference in relative movement between the plate and the can. It was found that the Cu-B₄C possessed greater plasticity than the mild steel can and elongated about a factor of three over the can movement. Thus, a 5-in. long Cu-B₄C pressing would have to be inserted into a 15-in. long can. This is not a satisfactory solution to the edge cracking problem and some new ideas are being investigated.

The dimensions for the Phoebus-2 control plates have been frozen and tooling to blank the desired shape from the rolled strip has been designed and is being built. The dies to form the control plate from the blank are in the design stage.

Mechanical Properties of Rolled Strip

Tensile specimens were machined by electrical discharge techniques (Elox) from Cu-50 v/o B₄C strip which had been rolled at 700 and 800°C, respectively, followed by rolling to size at 400°C. The pressings had been canned in mild steel prior to rolling. The results of the tests are given in Table 20. B₄C particles of -80 +100 mesh were used in the pressings. The strengths noted are considerably lower than observed on previous Cu-50 v/o B₄C strip made with a much finer B₄C particle with a wider particle size distribution (-100 +230 mesh). The

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Table 20. Properties of Rolled Cu-50 v/o B₄C Strip

<u>Sample</u>	<u>Rolling Temp., °C</u>	<u>Tensile Str., psi</u>	<u>Yield Str., psi</u>	<u>% Elongation</u>	
				<u>1/4-in. gauge length</u>	<u>1-in. gauge length</u>
R 13-1	700	4290	3080	8	4
R 13-2	700	4180	3130	8	3
R 15-1	800	3670	2560	8	3
R 15-2	800	3210	2390	8	4

ductility of these specimens, however, is higher than has been obtained on specimens of the same B₄C content tested earlier. Metallography indicated that the structure of the Cu-B₄C strip was free of fissures, indicating an advantage of the increase in rolling temperature from 600 to 700°C.

PHASE AND STRUCTURE STUDIES

Phosphides of Rare-Earth Metals

Several rare-earth monophosphides, as well as ScP, have been prepared and lattice parameters determined. The measured values are significantly different from values reported in the literature, as may be seen from Table 21. The differences may indicate a homogeneity range for the monophosphides.

Carbides

New Crystal Structures of Some Rare-Earth Dicarbides

The complex x-ray diffraction pattern found earlier for LuC₂ indicates tentatively a tetragonal structure with L even for the HOL and

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Table 21. Lattice Parameters of Phosphides

<u>Nominal Composition</u>	<u>a/o, Å (LASL Work)</u>	<u>a/o, Å (Literature)</u>
LaP	6.0358 ± 0.0005	6.025
PrP	5.9040 ± 0.0013	5.872
NdP	5.8638 ± 0.0005	5.838
SmP	5.7532 ± 0.0007	5.760
GdP	5.7296 ± 0.0005	5.623
DyP	5.6529 ± 0.0005	5.654
ErP	5.5990 ± 0.0005	5.606
YbP	5.5498 ± 0.0005	5.554
ScP	5.3095 ± 0.0008	5.312

HfL indices. In addition it has been found that HoC_2 , ErC_2 , and TmC_2 also become isostructural with LuC_2 when annealed at low temperatures (less than 1350°C). The tentative lattice parameters are given in Table 22. The compounds will be studied in greater detail to refine the lattice parameters and to determine transformation temperatures.

Table 22. Tentative Lattice Parameters of Dicarbides

<u>Compound</u>	<u>a₀, Å</u>	<u>c₀, Å</u>
HoC_2	6.20	27.2
ErC_2	6.17	27.4
TmC_2	6.14	27.0
LuC_2	6.07	27.0

The La-C System

A sample of LaC_2 has been examined by high-temperature neutron diffraction. Two modifications were observed, a low-temperature tetragonal phase which transforms to a cubic phase at about 1040°C . Both phases appear to be isomorphous with the analogous UC_2 phases.

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The Y-C System

A sample of approximate composition Y_3C has been examined by room-temperature neutron diffraction. The pattern can be indexed as cubic, $a_0 = 10.92 \text{ \AA}$. The structure is postulated to be a C-deficient NaCl-type, with an ordering of the C vacancies, resulting in a unit cell formed from eight Y_4C_x cells ($x \sim 1.5$).

The Ta-C System

The ζ -phase of Ta carbide has been investigated with high-temperature neutron diffraction. Preliminary results indicate that it forms from TaC and Ta_2C at temperatures above about $1500^\circ C$. Failure to form at lower temperatures may be due to kinetic effects. The expected transition of Ta_2C to a high-temperature form (presumably L'3 type) does not occur below about $1900^\circ C$.

The Tc-C System

The formation of a Tc carbide (presumably TcC) has been reported previously. The material exhibited an f.c.c. crystal structure with $a_0 = 3.985 \text{ \AA}$. The melting temperature of the sample (presumably the TcC-C eutectic) in a graphite crucible has been found to be $1835^\circ C$.

The Nb-Tc-C System

Approximately equal quantities of NbC and TcC (from the above sample) were mixed together and heated in a graphite crucible. The mixture was studied by cooling curve analysis at temperatures between 1600 and $2360^\circ C$. The only thermal arrest observed was at $1835^\circ C$. X-ray diffraction of the cooled sample gave a pattern which was completely resolved into two f.c.c. structures with lattice constants of 4.455 and $4.016 \text{ \AA}$. It seems probable that the larger parameter represents the NbC phase and that the small lattice parameter (4.455 vs $4.470 \text{ \AA}$ for NbC) indicates some solubility of TcC. The expanded lattice parameter for the TcC phase (4.016 vs $3.985 \text{ \AA}$) suggests some solubility of TcC in NbC.

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VI. MISCELLANEOUS RESEARCH AND DEVELOPMENT

INSTRUMENTATION DEVELOPMENT

Core Thermocouples

Four swaged W/W-26% Re thermocouples with 0.095-in. o.d. Ta sheaths and 0.020-in. diam wires were tested in the Mark VII graphite furnace. The purpose was to study the shunt effect in swaged BeO insulators and to see whether the swaged thermocouple wires would break due to thermally-induced stresses. Two thermocouples failed after 8 and 25 min whereas the other two lasted through 39 and 46 min runs, respectively, at temperatures above 3950°R in a He atmosphere. The shunting errors appear to be higher than with comparable unswaged thermocouples having fired BeO insulators.

Four 1/16-in. diam Mo-sheathed core material thermocouples were run for 1 h in H₂ and graphite at ~3100°R to study their drift with time. No measurable drift was observed.

Two 1/16-in. diam Mo-sheathed couples with vapor-deposited W coatings were tested in H₂ and graphite at 4560°R. They produced good signals for 8 and 10 min, respectively, before failure.

Exit Gas Thermocouples

Exit gas thermocouples are being designed for Phoebus-1B. They will be fed through dummy unloaded fuel elements as was done in Phoebus-1A but will be installed in clusters of three rather than one thermocouple

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per element. Two couples in each cluster will be used to measure fuel element H_2 discharge temperatures and the third will be placed ~ 9 in. above the core face to measure core H_2 discharge temperature. Seven clusters will be used to provide a radial profile for each type of measurement.

Three additional thermocouples will be fed through slat coolant holes and bent over the core to measure effluent temperature from outermost loaded elements. The thermocouples will be fabricated locally.

Copper-Constantan Thermocouples

The experimental work on Cu-Con thermocouple calibration stability was continued with a series of tests to determine if the instability is caused by thermoelement stress at the junction. Presumably, such stress could be caused by thermal expansion differences between the thermoelements and the sheath. Three of the eight couples used in the previous tests were opened and rejunctioned with exposed junctions. All eight thermocouples were cycled between LH_2 and room temperatures. The data indicate that exposing the junctions did not improve the calibration stability significantly.

Additional experiments were done to evaluate the calibration stability of swaged Cu-Con thermocouples recently fabricated against units which had been in stock for 3 to 4 yr. Comparisons were also made with couples fabricated from unstressed bare wire from the same lot as that used for the new swaged couples. In addition, new swaged couples with exposed junctions and with grounded junctions were tested to evaluate the possible contribution of the differential expansion of the sheath to calibration stability. The data obtained are shown in Fig. 40. The results may be summarized as follows:

1. The type of junction has no effect on calibration stability.
2. The bare wire follows the standard curve and it repeats well from run to run.

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Fig. 40. Results of copper-Constantan thermocouple tests compared with standard.

3. The new swaged couples exhibited significant deviation from the standard curve as well as calibration instability. Both effects were smaller than those observed with the old swaged thermocouples.

The following recommendations were made for the fabrication of Cu-Con thermocouples for cryogenic use:

1. 1/16-in. diam steel sheaths in the fully annealed state should be used.
2. The insulators should be crushable cylindrical MgO pellets approximately 1-2 in. long and 0.035 in. o.d. with two holes.
3. The 0.005-in. thermoelement wires should be threaded through the insulator holes, fitted into the sheath and the grounded plug junction TIG welded.

Platinum Resistance Thermometers

Calculations were made to predict the error due to γ heating in Pt resistance thermometers in Phoebus-1B. Some typical results are given below:

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<u>Type</u>	<u>Location</u>	<u>Heating Rate, W/g</u>	<u>Error, °R</u>
Rosemont 134 EH	Reflector Inlet	2.8	2.7
Minimum Mass Rosemont	Core inlet	5	0.2-0.6
Microdot film type	Core inlet	5	1-1.4

Pneumatic Devices

Pneumatic oscillators which have a frequency proportional to the square root of fluid temperature are being investigated for core exit gas temperature transducers. The devices can have high bandwidth and they appear to be quite insensitive to fluid pressure and oscillator material temperature.

Response tests have been made on pneumatic pressure lines filled at atmospheric pressure and terminated with either porous plaster of paris or many small tubes in parallel to avoid line reflections. The latter termination was successful in suppressing reflections but the plaster of paris did not work as anticipated. Tests will be made with H_2 to investigate the technique further.

REACTOR NEUTRONICS

Gamma-Ray Source Power in Phoebus-1 and Phoebus-2

A Phoebus nominal γ source power of 86 MW per 1000 MW of thermal power has been selected as a typical run parameter for those applications where γ variation with time needs not be considered. The previously recommended value of 74 MW for Kiwi reactors applied to short, single-step operation. The revised value assumes a startup profile similar to Kiwi-B-4E and Phoebus-1A.

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Fig. 41. Gamma source power for typical reactor operation and for single step operation.

Figure 41 shows the growth in γ -ray source power which would be expected during a single-step reactor operation at a constant 3.32×10^{19} fissions/sec. This is approximately the fission rate required to produce 1000 MW of thermal power in a Phoebus-1 reactor. Also included in the figure are points from Kiwi-B-4E and Phoebus-1A runs normalized to 3.32×10^{19} fissions/sec full power. For future Phoebus operations with comparable startup conditions, it is expected that the 86 MW nominal figure will be $\sim 10\%$ higher than the initial γ -ray source power and a few percent lower than the final value.

Heating from Cluster Plate (n, γ) Source

One-dimensional and two-dimensional (DTK and DDK) neutronic calculations have been utilized to estimate the number of n, γ processes taking place in the Cd and Ag of the cluster plates at the inlet end of Phoebus-1. The purpose of a Cd-Ag alloy for cluster plates is to attenuate the thermal neutron flux at the core inlet. Calculations show a more

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effective reduction of these neutrons than is observed experimentally (e.g., the DDK computed core inlet power is $\sim 50\%$ of that observed). This discrepancy is probably a result of representing the Cd-Ag as a uniform plate in the calculational model whereas in reality holes (to accommodate flow metering orifices and support rods), which constitute 40% of the surface, allow thermal neutron passage.

The DDK-computed radial distribution of Cd and Ag captures is given in Fig. 42. These capture rates provide γ -ray source input for QAD point kernel calculations of γ heating rates. The resulting heating across the core inlet is shown in Fig. 43 for four different materials of interest (C, Fe, Al, and Be). In Fig. 44 the various components of radiation heating are compared as functions of position along the reactor center line. It can be seen that radiation heating is significantly boosted within a few centimeters of the cluster plates.

Fig. 42. Radial distribution of Cd and Ag neutron captures in cluster plates.

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Fig. 43. Radial variation of inlet end heating for materials of interest.

Fig. 44. Comparison of radiation heating components along core axis at 1000 MW.

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CODES AND COMPUTERS

Hydrogen Properties--Digital Codes

The TAB tabular codes are in the final stages of completion. Source data for the TABTP code were received and final checkout work is being done. TABTP can be used to calculate H_2 properties from zero temperature and pressure to 5000°R and 5000 psia, respectively. Temperature and pressure are inputs to the code.

The TABHP code for calculating H_2 properties from enthalpy and pressure inputs has been checked at high temperatures where source data are available. Low temperature data have been ordered from NBS-Boulder.

A study was started to determine if a faster method could be devised to compute H_2 properties for the Phoebus TAF code. It appears that each property can be generated by a polynomial function of enthalpy in which the coefficients are polynomial functions of pressure. If the two-phase region is excluded, accuracy of about $\pm 1\%$ can be obtained. If this method proves successful, the running time of the TAF program will be cut approximately in half and the storage requirement will be reduced by about 3000 words.

Hybrid Computer Facility

Studies have shown that the most economical and technically satisfactory way of expanding the analog computer to meet Phoebus-2 analysis requirements is to add a small digital computer to the system. The proposed digital computer will have 40 analog input lines and 40 analog output lines. Each digital-to-analog converter can have its analog input switched from the 100-V reference supply to an analog variable voltage. This adds a two-quadrant multiplication option to all analog output channels. The digital computer will serve as a function generator which will update functions from 10 to 200 times/sec while the analog computer is integrating in real time. It can also be used for time delay simulation,

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transfer function measurement, describing function analysis, amplifier readout, partial differential equation solutions, and numerous other purposes. Requests for bids have been sent to vendors and should be returned by September 1. The computer should be installed around February 1966.

The digital computer seems to be capable of doing its primary functions of time delay and function generation easily. Because of this, most of the recent hybrid applications work has been on determining how many other additional calculations can be done simultaneously in real time. The problem is being investigated on the analog computer with the assumptions that (a) only nonlinear operations would be done on the digital computer and (b) the action of the digital computer could be approximated by an analog sample-and-hold circuit.

TWO-PHASE FLOW

A large amount of two-component, two-phase, noncryogenic pressure drop data contained on punched cards is being analyzed by machine. Before attempting any new correlation of the data, seven parameters have been looked at separately to determine which are important. The important parameters were found to be liquid and gas Reynolds numbers, pipe diameter (in some regions), pressure level, liquid viscosity, and flow pattern. Annular flow gave a higher pressure drop than all of the other patterns; no additional flow rate dependence was found. This phase of the work is now complete.

PLASMA RESEARCH

Arc Jet Experiments

An intermediate power Cs arc experiment has been constructed in order to investigate problems encountered in the design of the high power Li arc jet experiment proposed in Quarterly Report LA-3212-MS, p. 105.

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Fig. 45. Schematic diagram of cesium arc experiment.

As a result of the experience with Cs, the Li experiment will be operated vertically upwards. The Li will be supplied from a positive displacement piston with a bellows seal and the alkali metal will be introduced through the center electrode (cathode) of the coaxial arc geometry. All parts for the Li arc experiment are now on hand and assembly is proceeding.

In the meantime, the operation of the Cs arc has given interesting results. The experiment evolved into the design shown in Fig. 45 in which the essential features of the assembly are indicated. The anode and cathode are of Ta, and the insulator is of BN. No provision is included for measurement of the reaction on the arc electrodes and B_z coil assembly. Instead, the force on various objects in the downstream flow is detected. Force has been measured on a 1.5-cm diam Nb sphere, a Mo plate intercepting the entire beam and a screen of 0.005-in. diam W wires spaced 0.100-in. apart so as to form a 90% transmission grid. All of these force balances give the same result within the uncertainties for the drag coefficients of spheres and wires in a transitional flow regime. The power deposited in the electrodes and in the downstream beam catcher is determined calorimetrically by conventional methods.

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A typical line spectrum of the radiation from the flowing gas has the following composition: Cs II - 150 lines; Cs Unclassified (Cs II and Cs III) - 35 lines; Cs I - 5 lines; other alkali metals (Na, K, Rb) - 6 lines; and unidentified - 18 lines. These numbers indicate that the beam is completely ionized and probably possesses an appreciable doubly-ionized component since 185 of the 190 Cs lines originate 14 eV or higher above the ground state of Cs^+ .

The qualitative conclusions about the operation of this Cs arc with respect to the axial magnetic field and the arc current may be summarized as follows:

1. The force is independent of the strength of the axial magnetic field over the range of fields available (1200 G maximum). In this experiment, the axial magnetic field serves to inhibit arc attachment on the anode and to contain the plasma flow to the magnetic flux surface which originates within the confines of the anode.

2. The force increases with current but not in a regular or simple fashion, as seen in Fig. 46.

Measurement of the mass flow introduced into the arc, the force on the downstream pendulum, and the power in the jet are relatively straightforward. However, it is clear that an interpretation in terms of directed flow velocity is difficult. When $F/\dot{M}$ for all the experimental data, regardless of arc current, B_z , and arc voltage is plotted vs $\dot{M}$, Fig. 47 is obtained. The data may be represented by $F/\dot{M} = 85/\dot{M}$ sec for $\dot{M}$ values ranging over a factor of 100. At small $\dot{M}$, the kinetic energy in the jet, inferred from $F^2/2\dot{M}$, approaches and exceeds the calorimetrically measured jet power and in some cases even exceeds the electrical power input to the arc.

Accepting the force and power measurements as valid, the mass flow introduced into the arc from the piston is somehow augmented for small $\dot{M}$. The most likely sources of the experimental ambiguities are: recirculation and mass entrainment of Cs into the arc region; jet from an ambient low pressure Cs atmosphere; and Cs surface creepage to the lip of the anode.

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Fig. 46. Jet force vs arc current; solid circles are data with Cs piston turned off.

Fig. 47. Force/mass flow rate vs mass flow rate.

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VII. ROVER FLIGHT SAFETY

DESTRUCT EXPERIMENTS WITH CHEMICAL EXPLOSIVES

Beaded Fuel Fragmentation

Preliminary analysis of fuel samples fragmented while at 2500°C indicates the same particle size distribution as was obtained for the three room temperature samples. A second fragmentation has been performed at 2500°C but not yet analyzed.

The following additional fragmentation runs are planned to complete this series of experiments:

1. Fuel heated for 30 min at 2200°C to simulate conditions following a full-power operation.
2. Fuel heated for 3 h at 2500°C to simulate the conditions following a loss of coolant accident.
3. The feasibility of fragmenting a piece of Kiwi-B-4E fuel is being investigated. Present total β and γ contact activity of a 1-in. sample of this fuel is 3R/h.

NUCLEAR DESTRUCT CONCEPT

Beaded Fuel Studies

Intrinsic Thermocouples Studies

Miniature W/W-Re thermocouples (0.3-mil diam) have been successfully used on individual Rover fuel beads coated with 5-10 μ of W. Tests on a recent

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SNAPTRAN controlled excursion have shown excellent response characteristics with 62-100, 100-150, and 210-297 μ diam bead cores using PyC coatings of 25, 50, and 100 μ . Selected thermocouple units will be used in the SNAPTRAN-2.

Rover Type Fuel Samples

A group of selected Rover fuel samples similar to those employed in the external Kiwi-TNT studies will be placed next to the SNAPTRAN-2 destruct excursion now scheduled for November 19, 1965. The expected transient period is 0.3 msec and the energy release should produce 3.5×10^{15} fissions/g in the nearest samples. It is hoped that detailed information will be obtained on the breakup behavior of Rover fuel beads that is required to check calculations in progress.

Theoretical Studies

An examination of beaded fuel samples which have been fragmented by a fast nuclear transient indicates two possible breakup mechanisms for the beads: (1) melting and vaporization of the UC_2 core leading to a dissolution of the PyC containment shell by the formation of a UC_2 -C eutectic, and (2) direct fragmentation of the bead from stresses produced by high internal pressures. Fragmentation by pure pressure effects can occur if high vapor pressures or differential expansions can be obtained before all the particle and surrounding sheath is melted or weakened. On the other hand, if a substantial fraction of the sheath melts before all of the bead core is vaporized, the pressure buildup may not occur or be of a more moderate magnitude.

For the first case, approximate expressions have been derived for the energy available for a violent breakup of the fuel matrix in terms of the following variables: rate of energy deposition by fissions in the UC_2 , energy needed to heat the UC_2 to the temperature where vaporization sets in, the energy loss in phase transition (melting of UC_2

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and PyC sheaths), conductivity heat losses to the graphite matrix, and the duration of the reactivity pulse. Reactivity pulses of less than 2 msec half-width and more than 3×10^{14} fissions/g U^{235} appear necessary to initiate breakup of the matrix by this mechanism. The conductivity heat loss term is sensitive to geometric parameters such as the radius of the UC_2 sphere, and the thickness of the PyC coating as well as to the pulse length.

Calculations are in progress to determine the stress rupture conditions. A code has been prepared for the MANIAC and is now being "debugged."

The quantitative results for either set of calculations is highly dependent on a knowledge of the physical properties of the materials involved under the proper temperature conditions. Work is in progress to accumulate and tabulate such properties as Young's modulus, Poisson's ratio, coefficient of linear expansion, coefficient of heat conductivity, density, specific heat, fracture stress, and fracture strain for UC_2 , PyC, and matrix graphite. The highly anisotropic properties of PyC require that this material be so treated in any computations.

KIWI-TNT

The frame associated with maximum γ -ray excited fluorescence has been established in one Fastax film of Kiwi-TNT. Color prints of frames around the maximum fluorescence were made to enhance the blue glow. This independent identification of peak power together with the time code on the Fastax film was used to check the time of peak power determined from the neutronic measurement recorded by the data system. These data appear to agree within 100 to 200 μ sec for the time of peak power depending upon where the peak is determined from the various neutronic measurements. This does not necessarily mean that the Kiwi-TNT timing is correct since there may still be compensating errors in both determinations of time of peak power.

The emergent neutron spectrum for Kiwi-TNT is shown in Fig. 48, and the significant data are listed in Table 23. The third column is the collimated time-integrated neutron flux corrected for neutron attenuation of the collimator which was at 645 ft from the source. Other columns are self explanatory.

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Table 23. Kiwi-TNT Neutron Spectrum

Neutron Energy Interval, MeV	Tracks Measured	Integrated Flux		Mean Free Path ($\pm 5\%$),m	Source $\Delta Q/\Delta E$	
		10^6 neutrons $\text{cm}^2\text{-MeV}$			10^{16} neutrons MeV	
1-2	322	304 ± 19		100	1060 ± 170	
2-3	125	156 ± 15		135	327 ± 40	
3-4	28	45 ± 8		110	131 ± 28	
4-5	32	60 ± 11		130	132 ± 28	
5-6	19	41 ± 10		145	78 ± 20	
6-7	9	21 ± 7		160	35 ± 13	
7-8	3	8 ± 5		150	14 ± 9	
8-9	1	3 ± 4		155	5.3 ± 7.4	
9-11	1	1.7 ± 2.4		160	2.8 ± 3.9	
		$- 1.7$			$- 2.8$

Fig. 48. Energy spectrum of neutrons escaping from Kiwi-TNT.

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VIII. ROVER FACILITIES ENGINEERING

FY 1964 Rover Construction

Furnace Facility, Building DP-207: Installation of the four furnaces in Building DP-207 is scheduled for completion in mid-November. Drawings are 99% complete for installation of another furnace in Building DP-206.

Subassembly Building Addition, TA-18: Construction is 93% complete and is scheduled to be finished on September 23.

Ultrasonic Cleaning Facility, TA-18: Title II engineering on the building will be reviewed in mid-September. Shop drawings on the ultrasonic cleaning equipment have been approved and returned to the vendor.

FY 1965 Rover Construction

Nondestructive Test Additions, TA-8: Construction of the two building additions is complete.

Mechanical Test Facility Addition, TA-46: Construction is scheduled for completion early in December.

Laboratory Modifications for Graphite Research, Building SM-29: Some equipment has been delivered and is being installed. Design of the balance of the required modifications is 80% complete.

Standards Laboratory, TA-46: Design is 65% complete.

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Cooling Water System Replacement, TA-56: Design is 60% complete.

Core Support Test Facility, TA-46: Construction is scheduled for completion in late December.

Gaseous Hydrogen Supply System, TA-3 to TA-46: An A-E has been selected by the AEC to engineer the pipeline installation between TA-3 and TA-46. Design of the terminal facilities, which is being performed at IASL, is 45% complete.

Remote Liquid Hydrogen Facility, TA-46: This facility has the lowest priority of the eight Phoebus subprojects and design has not yet been started.

Pulsed Accelerator Building, TA-18: Bids were opened on June 17, and the lower of the two bids received was 18% over the government estimate. Both bids were rejected and the A-E was directed to reduce the cost of the facility. Revised drawings have been issued and new bids will be opened on September 9.

FY 1966 Rover Construction

Projects tentatively proposed for FY 1966 Rover funding are as follows:

Laboratory Modifications, Wing 3 Basement, Building SM-29.

Chemical Milling Facility Addition, Building SM-39.

Computer Facility Installation, Building WA-42.

Liquid Hydrogen Remote Facility, TA-46.

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Electric Power Supply

LASL has requested the AEC to investigate alternative methods of supplying additional electrical power to the TA-46 vicinity. Consideration is being given to the procurement of a 1500-kW motor generator set to be installed in this area. The installation, together with large electrical loads installed in recent years, will necessitate some redistribution of power, or a new source of power to TA-46. The amount and source of funding to meet the increasing electrical requirements have not yet been determined.

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IX. PUBLICATIONS

"Cryogenic Technology in the Nuclear Rocket Program," Intern. Congress of Refrigeration, Munich, Germany, 1963. Intern. Inst. Refrig., 1965, p. 145.

"Large Volume Operational Room Inerting," Advan. Cryog. Eng., 10, Pt. 1, 273 (1965).

"Pressurization Analysis of a Large-Scale Liquid-Hydrogen Dewar," *ibid.*, 10, Pt. 2, 284 (1965).

"Probing Experiments on Pressure Oscillations in Two-Phase and Supercritical Hydrogen with Forced Convection Heat Transfer," *ibid.*, 10, Pt. 1, 305 (1965).

"Detection of Density Variations in Flowing Two-Phase Hydrogen," *ibid.*, 10, Pt. 1, 323 (1965).

"Experimental Study of H₂O-LH₂ and H₂O-LN₂ Heat Exchangers," *ibid.*, 10, Pt. 1, 375 (1965).

"Description of the Kiwi-TNT Excursion," Trans. Am. Nucl. Soc., 8, 126 (1965).

"Analysis of the Kiwi-TNT Experiment," *ibid.*, 8, 126 (1965).

"Kiwi-TNT Evaluation of Environmental Effects," *ibid.*, 8, 127 (1965).

"Pin Technique for Displacement Measurements in Kiwi-TNT," *ibid.*, 8, 127 (1965).

"Application of Miniature Intrinsic Thermocouples for Reactor-Transient Diagnostics," *ibid.*, 8, 128 (1965).

"Behavior of Coated-Particle Fuels in a Large Nuclear Transient (Kiwi-TNT)," *ibid.*, 8, 129 (1965).

"Los Alamos Coupled Reactor Experiments: Techniques," *ibid.*, 8, 222 (1965).

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"Instrumentation at the Los Alamos Critical Assembly Laboratory,"
IEEE Trans. Nucl. Sci., 11, 358 (1964).

"Effects of Prestrain on the Tensile Properties of Graphite," Carbon, 2,
269 (1964).

"Large Scale Cryogenics in the Nuclear Rocket Program," Am. Chem. Soc.
Abstracts of Papers, 149, 7L (1965)(Abstract).

"Forced Convection Heat Transfer to Cryogenic Hydrogen," ibid., 149, 8L
(1965)(Abstract).

"Nondestructive Inspection of Nozzles of Nuclear Rockets," Materials
Evaluation, 23, 32 (1965)(Abstract).

"Nuclear Rockets," Intern. Sci. Technol., No. 43, 58 (1965).

"Particle Size Distribution from a One-Ninth-Scale Rover Reactor
Axial-HE Destruct," LA-3214-MS.

"Effects of Adding Hydrogenous Material to Kiwi Reactors," LA-3227-MS.

"Proceedings of an Advanced Nuclear Propulsion Symposium," LA-3229-MS.

"Static Physics of Rover Reactors," LA-3231-MS.

"Possible Remote Maintenance and Repairs on Reactors at NRDS," LA-3242-MS.

"Power Density Asymmetries in Coupled Core Reactor Systems," LA-3283-MS.

"Investigation of Coupled Phoebus Cores," LA-3284-MS.

"Integral Gamma and Neutron Measurements on the NRX-A-2 Reactor,"
LA-3296-MS.

"Application of Miniature Intrinsic Thermocouples for Reactor-Transient
Diagnostics," LA-3313-MS.

"Description of the Kiwi-TNT Excursion," LA-3350-MS.

"Some Biological Aspects of Radioactive Microspheres," LA-3365-MS

"Pin Technique for Displacement Measurements in Kiwi-TNT," LA-3388-MS.

"Integral Gamma and Neutron Measurements on the Kiwi-B-4D-202 and
Kiwi-B-4E-301 Reactors," LA-3286.

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"Radiochemical Measurements on Kiwi-TNT," LA-3290.

"Integral Gamma and Neutron Measurements on the Kiwi-TNT," LA-3304.

"Kiwi-TNT 'Explosion'," LA-3351.

"The Behavior of Coated Particles in a Large Nuclear Transient (Kiwi-TNT)," LA-3367.

A draft version of LA-3358-MS, "Nuclear Rocket Safety Neutronics Summary Report," has been released for limited distribution as Vol. V of the Washington sponsored "Rover Flight Safety Program Preliminary Review."

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