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SOME MAJOR FUEL-IRRADIATION TEST FACILITIES OF THE OAK RIDGE NATIONAL LABORATORY

D. B. Trauger

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

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APRIL 1964

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ABSTRACT

Irradiations of test fuel specimens and experimental fuel elements are conducted both in capsules and in forced-convection-cooled loops. The design of equipment suitable for irradiation tests pertinent to the development of boiling- and pressurized-water, gas-cooled, sodium-cooled, and molten-salt reactors is described briefly, with particular emphasis on test capability.

The capsules utilize thermal conduction through sodium or NaK, gas-filled annuli, and graphite for heat removal from the fuel element surface. Six basic designs have been employed, with many variations, in conducting over 125 separate irradiation experiments. Capsule features include external pressurization to 900 psia, sweep gas for fission-gas removal, fission-gas sampling and daughter-trap collection for gamma-ray spectrometer analysis, continuous flux monitoring and control, and measurement of temperatures up to 4000°F.

The loop facilities described are: (1) a pressurized-water loop for operation up to 2500 psia and 625°F with heat removal up to 300 kw; close control is provided over water chemistry; (2) two helium-cooled loops capable of operation up to a gas temperature of 1500°F, a system pressure of 300 psia, and fission and gamma heating of 60 kw; other coolants can be accommodated, and the loops are designed to operate with fission-product contamination when necessary; (3) a compact loop design for recirculating molten-salt fuels at high temperatures.

Design features to meet safety requirements, alteration of equipment to accommodate changing program needs, and factors affecting the economics of operation are discussed briefly. The close relationship needed between the irradiation test laboratory and fuel development programs is indicated. The usefulness of assistance from other related groups in a large laboratory complex is mentioned. Finally, shop facilities are described for meeting the exacting needs of irradiation capsule assembly.

SOME MAJOR FUEL-IRRADIATION TEST FACILITIES OF THE OAK RIDGE NATIONAL LABORATORY

D. B. Trauger

INTRODUCTION

The Oak Ridge National Laboratory from its inception has been engaged in the development of reactors and reactor fuels. Important to this phase of ORNL work is the testing of fuels under conditions which simulate the intended service in a power-producing reactor. Achievement of appropriate test conditions was first made possible by the development of test reactors which produce high neutron fluxes. Early tests were conducted in the LITR[1] and the MTR;[1-2] later experiments were designed to utilize the ORR[3] and the ETR,[4] which afford more versatile arrangements for engineering-scale tests. ORNL irradiation test rigs are now concentrated in the ORR and LITR, where various test positions are utilized, including in-core, poolside, and beam-hole facilities. Other reactor space is used as required to obtain additional space or particular features.

The text of this report is intended to provide a brief but basic description of the irradiation facilities. It is hoped that it will be particularly useful to those engaged in related fields, such as fuel development, and for program planning. This report also illustrates the diverse equipment which is available and indicates the capability of a national laboratory to conduct the irradiation-testing phase of reactor development programs. For those directly interested in irradiation test work, this report will serve only for reference purposes; it is not intended to provide the detail necessary for improvement or duplication of test equipment.

The fuel-irradiation test facilities described have been the responsibility of the Irradiation Engineering Department of the Reactor Division. They were designed to provide appropriate environments for several power-producing reactor systems, and their primary application has been to evaluate fuel and fuel element concepts which are advanced beyond proven practice. Experiments are conducted in these facilities to determine the effects of nuclear processes, including radiation damage, fission-product generation, and transmutation, particularly as related to other variables. Important nonnuclear factors include temperature, thermal stress, pressure stress, differential thermal expansion, and chemical and metallurgical properties. Specific problems involve changes in metallurgical structure, interactions between fuel and its cladding or container, buildup of pressure by volatile fission products, and the movement or redistribution of radioactive materials within the fuel system. The equipment described in this report has been used for the investigation of variables affecting fuel element design, for proof testing of prototype fuel assemblies, and for studies involving reactor coolants. Reference is made in the text to documents which describe the program requirements and fuel development work for which the irradiation facilities were designed.

Equipment is available for tests of both the solid and the liquid fuels under development for use in thermal and fast reactors. Both liquid and gas coolants can be employed. Most of the irradiation rigs have been utilized repetitively, with both major and minor revision to accommodate changing program needs. In each revision, capability for the earlier purpose was retained where possible, and thus highly versatile equipment has been developed. A list of the irradiation facilities, identified by the test reactor, and the number of experiment stations is given in Table 1. The ETR and MTR capsules are in the reactors of corresponding title, which are located at the National Reactor Testing Station in Idaho; the others are located at ORNL.

Varied technical skills are required to effectively plan irradiation test work. Designers, experienced analysts, project engineers, and trained operating crews comprise the team for conducting experiments. Extensive assistance from other groups at ORNL is used to complement the effort of the Irradiation Engineering Department and provide strong support. This includes work in reactor analysis, radiation shielding, metallurgy and ceramics, welding and brazing, inspection, analytical chemistry, instrumentation, health physics, and reactor operations. Related tests frequently are conducted by other groups and coordinated with the irradiation studies. Shop facilities and other services from the Y-12 and ORGDP plants are also used extensively. Test programs may be initiated and directed either by the Irradiation Engineering Department or, more frequently, by other ORNL groups engaged in reactor or fuel development.

Considerable attention is given to reliability of equipment and safety. The principle of double containment by use of independent vessels or structures is followed to ensure that radioactivity is not released in the event of accident or malfunction of equipment. Very few deviations from this principle are permitted, and monitoring normally is provided to show that both the primary and secondary vessels are intact. Most experiments utilize the reactor safety system to prevent serious accident conditions in the event of equipment malfunction, but ultimate safety is provided by containment. Vessels are built and inspected according to the standards of applicable codes.[5-8]

Irradiation test equipment in general is difficult or, in many cases, impossible to alter or repair during or following operation. Out-of-pile tests of both equipment and experimental elements are therefore conducted whenever practical and where significant conditions can be attained. Thorough checking and evaluation of in-pile equipment contribute greatly to reduction of costs by assurance of successful experiments through satisfactory operation. Despite precautions, many difficulties have been encountered in conducting the irradiation experiments described. It may be stated conservatively, however, that this equipment has performed well and, in general, has met its test requirements satisfactorily.

Table 1. Capabilities of Irradiation Test Facilities[a]

Facility	Number of Stations	Maximum Number of Test Elements	Maximum Fuel Dimensions (in.)		Maximum Temperature (°F)		Maximum Thermal Neutron Flux (neutrons/cm^2·sec)	Station Maximum Power (kw)
			Diameter	Length	Fuel Surface[b]	Coolant		
LITR capsules	7	28	0.375	3	1300[c]	400	2×10^{13}	1
ORR poolside capsules	8	8	3	12	1600[d]	1600[e]	7×10^{13}	20
ETR capsules	14	14	0.75	18	1600	1600[e]	8×10^{13}	30
ORR eight-ball facility	1	1	1.5	16	2500	2500[e]	1×10^{14}	20
ORR helium loop No. 1	1	1	0.875	18	1600[f]	1400	8×10^{13}	60
ORR helium loop No. 2	1	1	2.75	9	2500[g]	1500	1×10^{13}	20
ORR pressurized-water loop	2	33	1.5	19	700	625[h]	7×10^{13}	150[h]
MTR capsules and loop	1	6	3	6	2500[g]	1600[e]	1×10^{14}	30

[a]Not all maximum limits are attainable simultaneously.

[b]Fuel central temperatures can be measured in all facilities except the ETR capsules; maximum temperature measured to date is 4200°F.

[c]Capsule temperature; fuel outer surface may be much higher, ~3000°F maximum to date.

[d]Limited by cladding material; value given is for stainless steel; 2500°F can be achieved for graphite-matrix fuels.

[e]Static gas in thin annulus.

[f]Limited by cladding material; value given is for stainless steel.

[g]Limit determined by nature of fuel under test; value given is nominal for graphite-matrix fuels.

[h]Loop designed for 650°F and 2500 psi; present in-pile tube is limited to 625°F and 2250 psi; total loop capacity is 300 kw.

The design, and therefore description, of irradiation equipment necessarily includes consideration of hot-cell facilities and techniques. Although some reference is made to hot-cell requirements, detailed discussion of postirradiation examinations is outside the scope of this report. However, for completeness, references are listed which describe ORNL hot-cell equipment and the facilities used with this irradiation equipment. The ORR hot cell to which experimental equipment from the reactor core or poolside can be removed directly through the pool without the use of casks or shielding other than the pool water is described in ref. 9. This cell location provides convenient means for early inspection of irradiated equipment. A large cell has been provided for handling beam hole and other major assemblies and for temporary operation of radioactive equipment of small pilot-plant scale.[10] Specialized equipment for sectioning materials and detailed examination has been provided in cell No. 6, which can accommodate alpha contamination.[11] Smaller cells are available for radiography and other analytical work. A new facility is nearing completion which will accommodate a large volume of work, including close inspection, specialized disassembly, and detailed examination.[12]

Initial dismantling of equipment irradiated at the MTR is handled in cells at NRTS. Many of the experimental assemblies listed in this report were examined in hot cells at GEVAL (General Electric Vallecitos Atomic Laboratory) and at BMI (Battelle Memorial Institute).

DESCRIPTION OF FACILITIES

The two classifications, capsules and loops, employed in describing irradiation test equipment are distinguished by the method of heat transfer from the fuel surface. In capsules, heat transfer is principally by conduction, whereas loops employ convection cooling, usually by a recirculating coolant forced by pumps or compressors. By their simplicity, capsule facilities are less costly to construct and operate, but they do not simulate the reactor service as realistically as loops. Various arrangements for both types of equipment are employed at ORNL. Each facility has been somewhat specialized to provide for specific test needs. The various units are complementary so that a major fuel development program can be conducted quickly with adequate irradiation test support. Replication of the simpler facilities provides capacity for handling several programs simultaneously.

The LITR capsules are small test systems designed particularly for accelerated experiments or for screening of materials. Although cooled by forced convection, the compressed air is used only for convenience. Seven stations are available, and each is capable of containing as many as four encapsulations of fuels, including metals, alloys, ceramics, such as UO_2, UC, and UN, and coated particles.

The ORR capsules are highly versatile units in which many different kinds of fuel can be irradiated under more complex test conditions. A wide range of environments can be provided for fuel elements, including gases and liquid metals, high external pressures, and thermal cycling. Full-size fuel sections (except as limited in some cases by length) can be accommodated so that highly definitive tests are possible. The ORR eight-ball and the ETR capsule units have similar capabilities but are limited in size and in neutron flux control by their locations in reactor core and reflector positions, respectively. However, these locations provide higher neutron flux levels and excellent heat-removal capabilities for conducting tests at high power densities.

The facility now at the MTR was developed for a complex loop operation before the ORR was available and has since been altered to provide diverse capability to meet many fuel test requirements. Both package loops and capsules can be accommodated at the MTR. The HB-3 beam hole has been used for the experiments; however, the out-of-pile equipment could be used with other test positions.

The ORR loops afford more complete simulation of reactor conditions, since dynamic forces, nonuniformity of cooling, and the effect of expected impurities in reactor coolants can be included. The two gas loops complement each other in providing a considerable range of neutron flux intensity, specimen size, heat removal, gas coolant chemistry, and simulation of reactor system features. The pressurized-water loop provides many features of both pressurized- and boiling-water reactors and can handle elements having large heat-generation ratings. Operation of the three loops in common effects considerable savings in operator and maintenance costs. Furthermore, the three loops and, to some extent, the capsules also utilize common equipment and services. When savings are accomplished in this manner, long-range planning is desirable because each facility is affected by the program for the others. Important advantages, however, are the justification of greater service facilities and pooling of technical talent. Experiences gained by one task engineer in a closely knit group directly strengthens the work of others.

Figures 1 through 4, respectively, show plan views of the ORR, LITR, MTR, and ETR reactors and the locations of equipment described. The complexity of an actual installation is illustrated in the photographs of the ORR pool in Figs. 5 and 6.

Capability now exists for conducting approximately 50 simultaneous engineering-scale irradiations of experimental nuclear reactor fuels. Each may be conducted under a unique set of conditions, although several may arbitrarily be made essentially identical for replication or for comparative experiments. The heat-removal capabilities of individual facilities and the available neutron fluxes are given in Table 1.

Tests may be conducted with various coolants in contact with fuel or cladding, including air, argon, CO_2, He, N_2, Na, NaK, and water. ORR loop No. 1 is adaptable to hydrogen cooling, although irradiation tests with this gas have not been conducted to date. Instrumentation is available to measure fuel temperatures reliably up to 3000°F and with less certainty to 4000°F. Independent control of both neutron flux and temperature has been achieved for some of the facilities, including both capsules and loops. The general capabilities are given in Table 1. The equipment described in this report has been utilized for the irradiation of more than 300 separate fuel capsules during the past five years.

In addition to the specialized facilities, hydraulic rabbit tubes and noninstrumented capsules in test reactor core positions may be used for irradiations. Rabbit facilities are satisfactory for many irradiations and are utilized when possible because relatively little cost is involved.[13] However, the limited range of conditions achievable and the obvious simplicity of the noninstrumented assemblies place them outside the scope of this report. Tests also may be conducted by placing experimental elements directly in the core of a reactor test facility or in a power reactor. Such tests are limited to relatively well-proven devices, since a large installation might be adversely affected by failure of the element. Also, it is not possible to vary test conditions in a power reactor adequately for many needs of development programs.

Not all irradiation equipment of ORNL has been included in this report. In general, the larger equipment currently utilized in direct support of Reactor Division programs is described. Many other facilities are available for materials studies and for testing specific properties of fuels.[13]

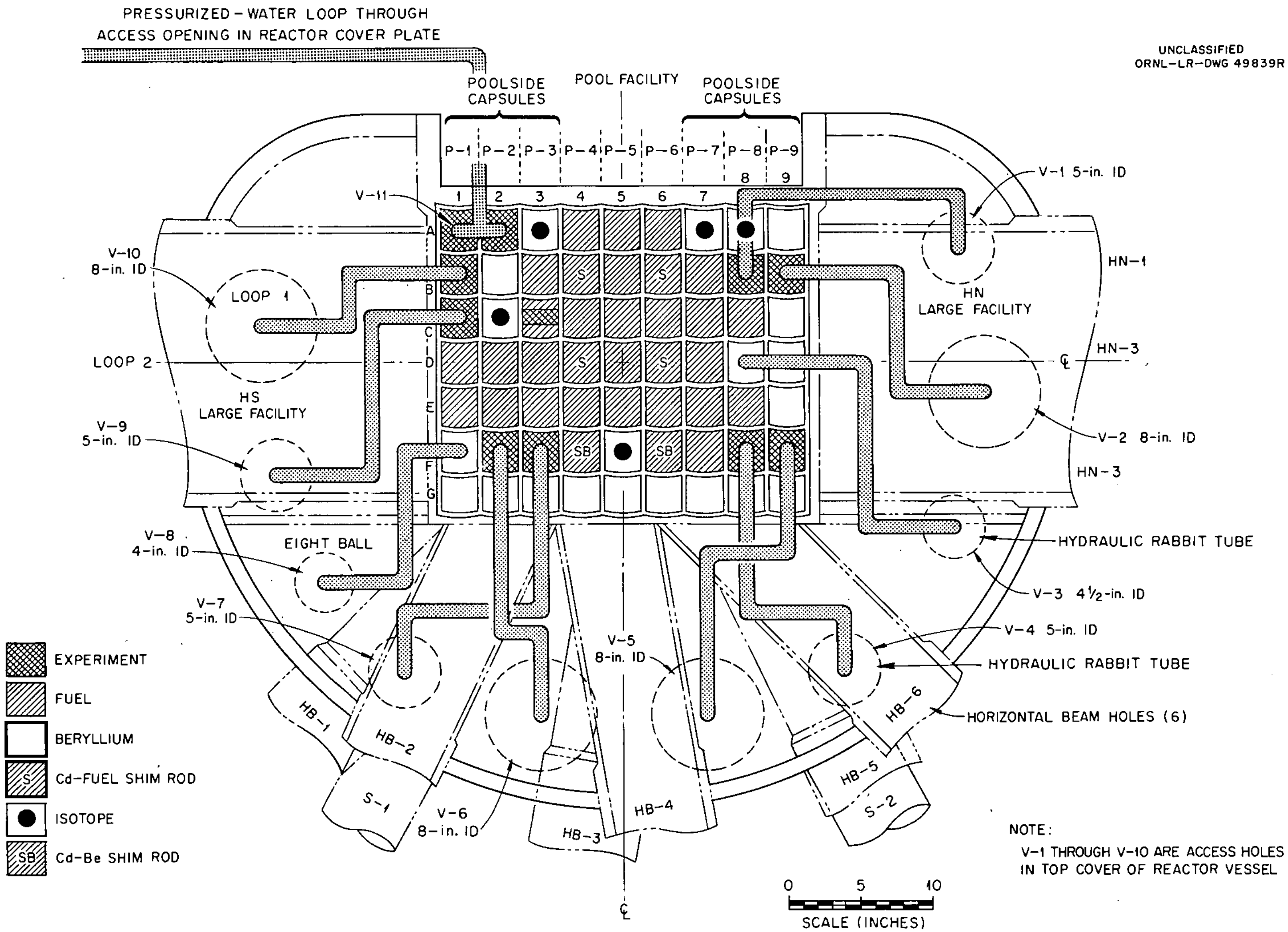

Fig. 1. Plan View of ORR Showing Location of Irradiation Equipment and Fuel Loading on June 30, 1963.

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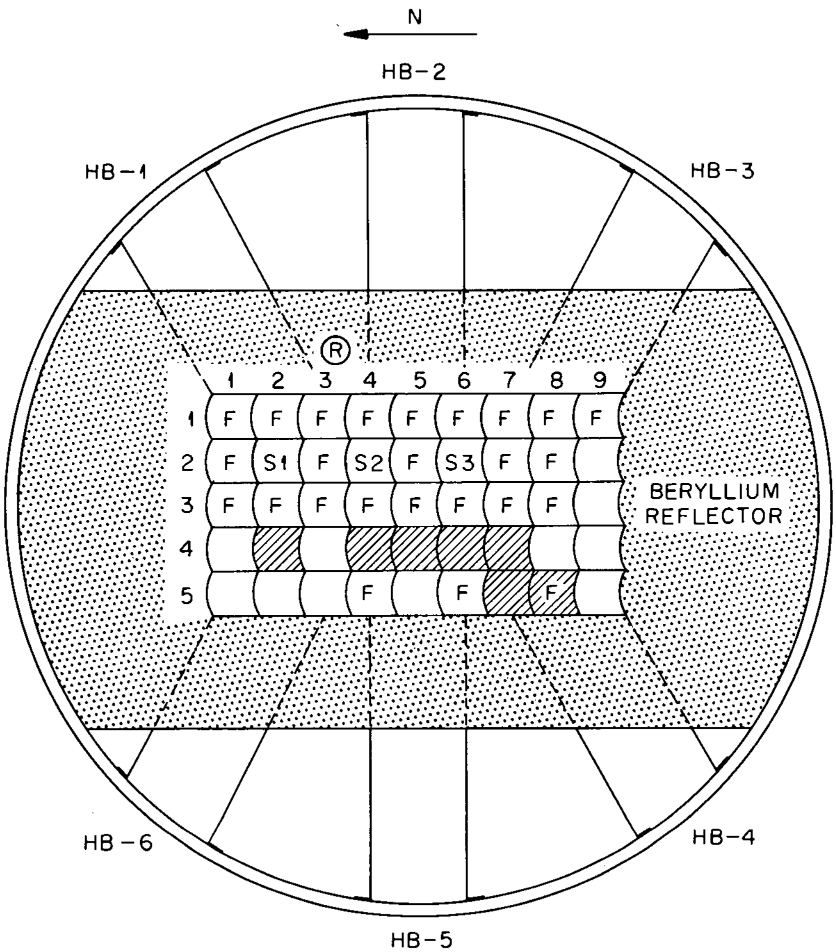

F — FUEL ELEMENT (INCLUDING PARTIAL ELEMENTS)
S1, S2 AND S3 — SHIM RODS
R — REGULATING ROD
SHADED POSITIONS ARE USED FOR AIR–COOLED CAPSULES

Fig. 2. LITR Lattice Pattern and Locations for Experiments.

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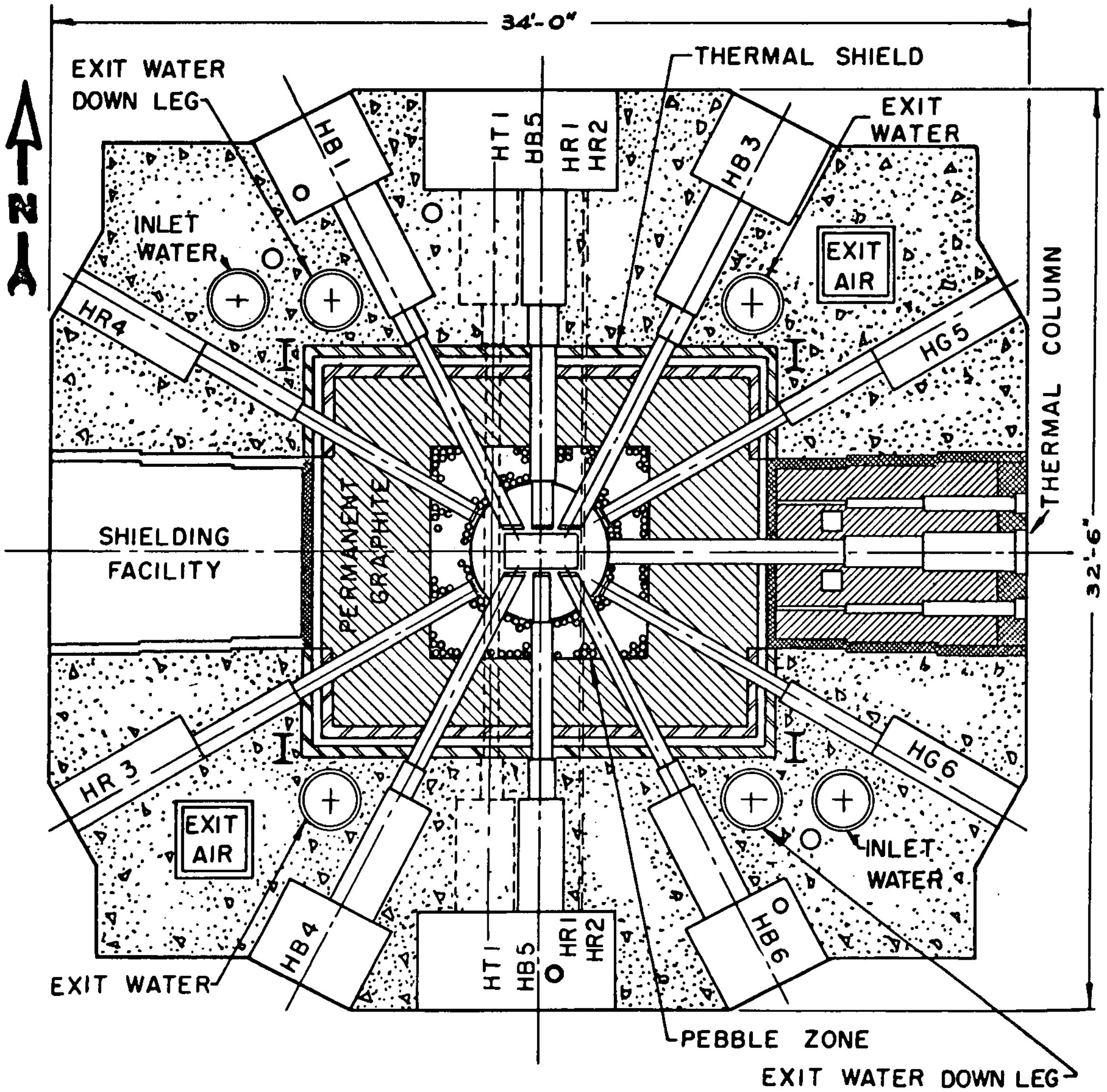

Fig. 3. MTR Horizontal Section Showing Locations for Experiments.

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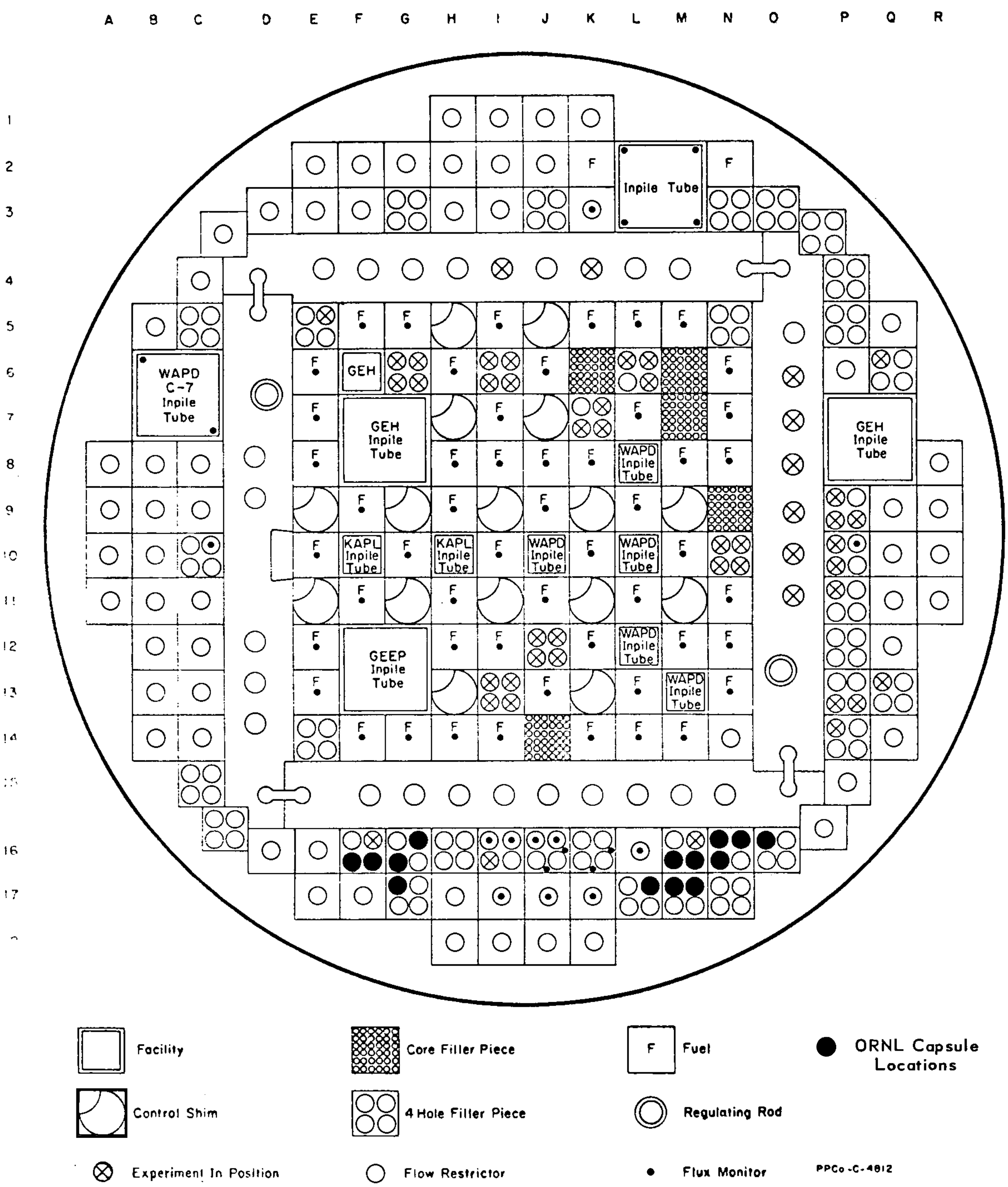

Fig. 4. ETR Core Showing Location of ORNL Capsules with the Fuel and Experimental Loading for Cycle 51B.

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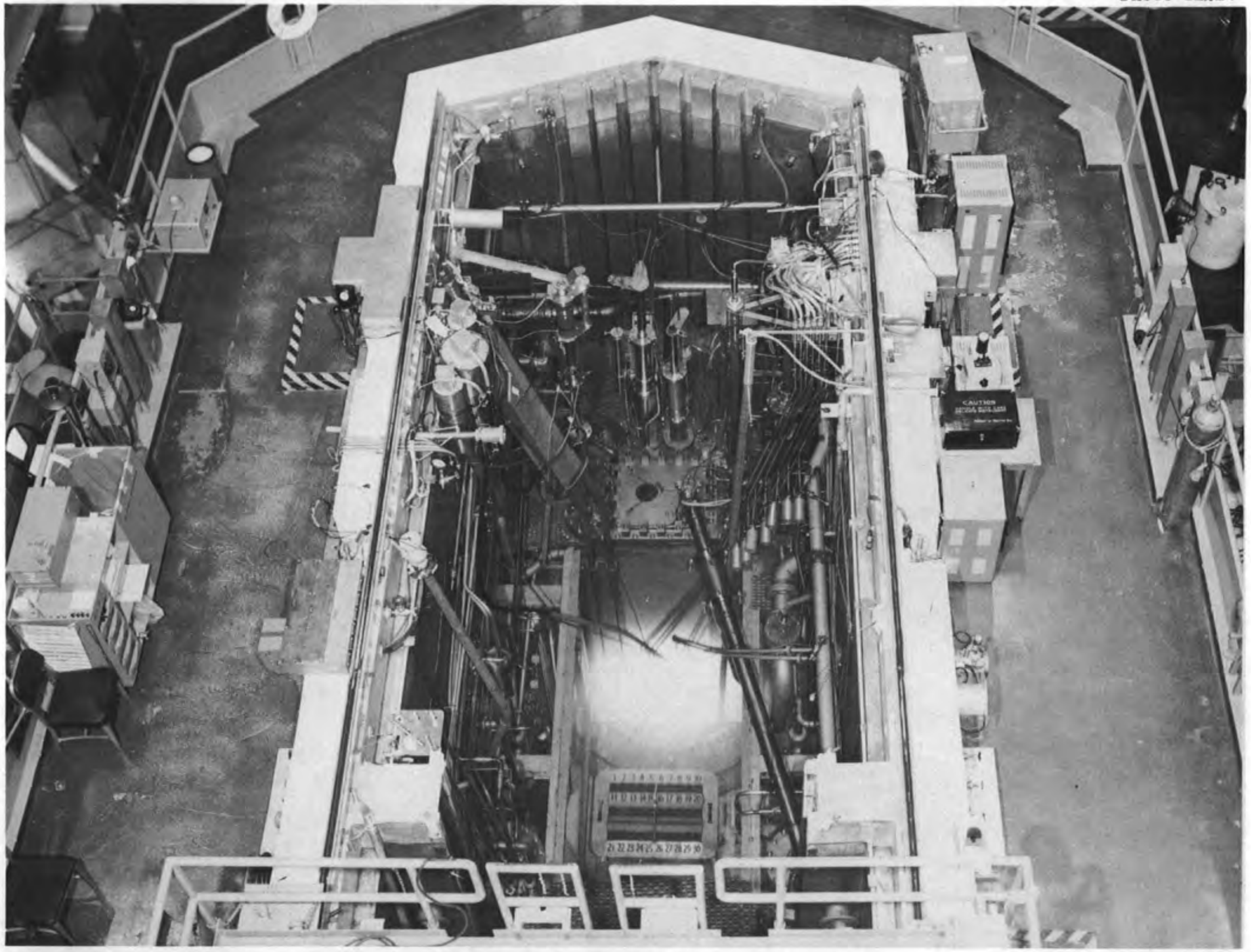

Fig. 5. Overall View of ORR Pool Area Showing the Many Experimental Facilities Now Installed. Other equipment, particularly for beam-hole experiments, is located on the floor below, on the lower balcony, and in the basement.

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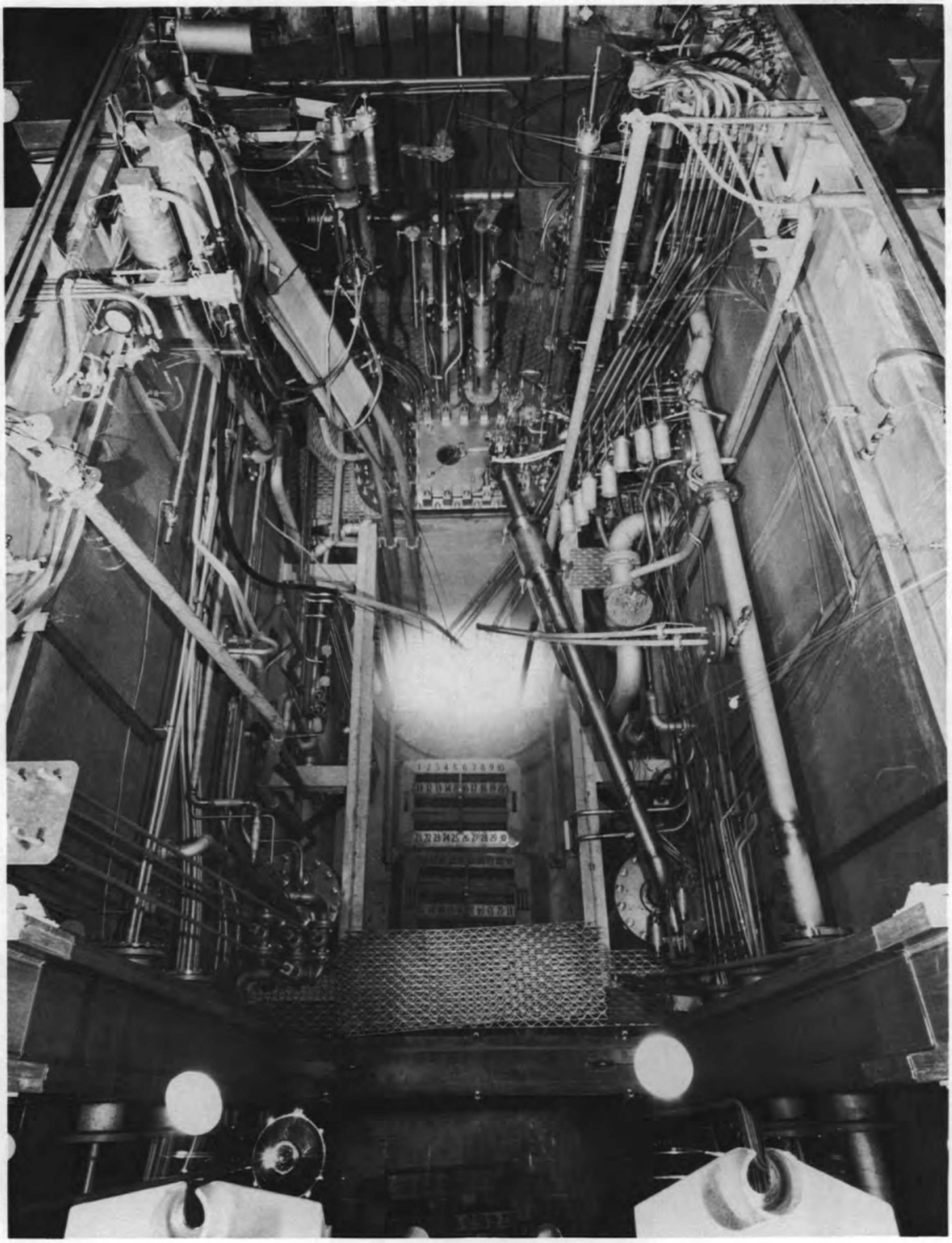

Fig. 6. Enlarged View of Irradiation Equipment Installed in the ORR.

ORR Poolside Capsule Facility

The ORR has a large high-flux irradiation facility outside the reactor tank. This was achieved by providing a flattened and indented section of the reactor tank adjacent to one side of the core. Since the ORR tank is immersed in a large pool of water, direct access is available to a large volume having a high neutron flux density. The water shielding pool provides visibility and space for movement of equipment without restriction. This arrangement has proved most useful for conducting capsule tests.

The poolside capsule irradiation facility is shown diagramatically in Fig. 7. It was developed for the EGCR fuel-irradiation program[14,15] but has since been extended for testing several configurations and sizes of both clad and all-ceramic fuel elements.[16-19] As many as eight separate fuel assemblies can be accommodated simultaneously in separate containers; however, when the fuel specimens exceed 1 in. in diameter, their number must be reduced.

Basically, the irradiation capsules are of concentric double-wall metal construction and utilize either NaK or graphite to conduct heat from the fuel specimen to the inner container. A thermal barrier in the form of a gas gap between the inner and outer containers provides the resistance necessary to achieve high temperatures during irradiation. The heat energy is rejected from the outer wall to the reactor pool. Measurement of gas pressure in the annulus is a means for monitoring the integrity of the vessels, which also serve as containment for safety requirements. Fuel element cladding surface temperatures up to 1600°F can be attained in present capsules with the specimen immersed in NaK, as shown in Fig. 8. Higher surface temperatures can be achieved at the test fuel element surface by using other materials of construction or by placing the element inside a second gas-filled annulus. Temperatures are measured by thermocouples inserted in the NaK or the graphite inner structure.

Irradiations of fuel in a graphite matrix have been conducted at surface temperatures up to 2500°F. A capsule for irradiating fueled-graphite spheres is shown in Fig. 9. The basic design features of this capsule are similar to those for the eight-ball capsule described in a later section of this report. Heat ratings of 70,000 to 150,000 Btu/hr·lin ft, depending on the capsule diameter, can be accommodated. Thermal- and fast-neutron fluxes, of 7×10^{13} and 5×10^{13} neutrons/cm^2·sec respectively, are available.

For clad fuel elements, application of the external collapsing forces to be experienced in gas-cooled reactor atmospheres has been provided by pressurizing the helium over the NaK surface. Pressures as high as 850 psi have been used. For temperature measurement in hollow cylindrical fuel pellets, molybdenum thermocouple wells brazed into the element end cap extend to the midplane elevation. Tungsten-rhenium thermocouples have been used in these wells to measure UO_2 fuel central temperatures

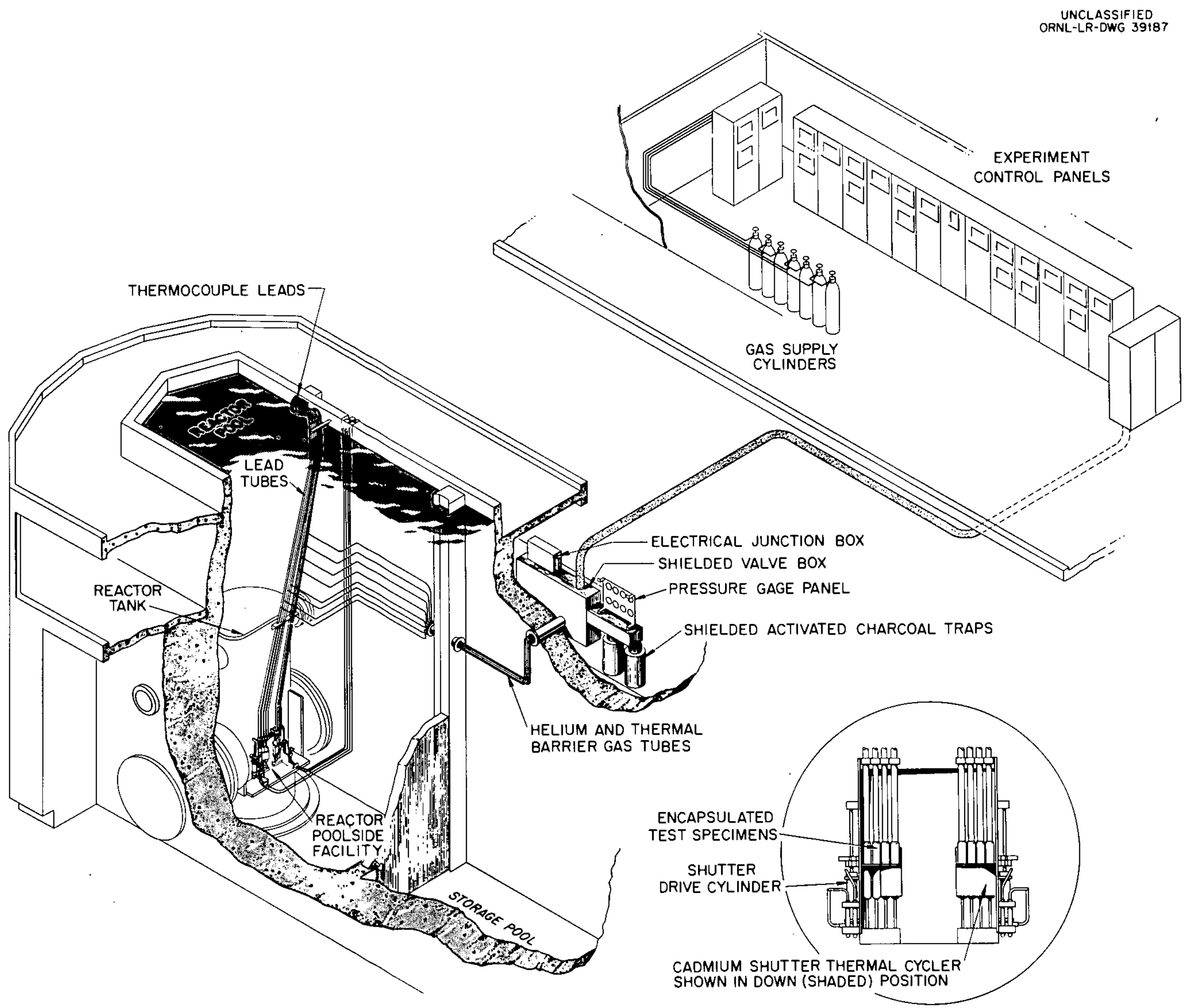

Fig. 7. Experimental Facilities for Irradiation of Full-Diameter Prototype Fuel Capsules in the ORR.

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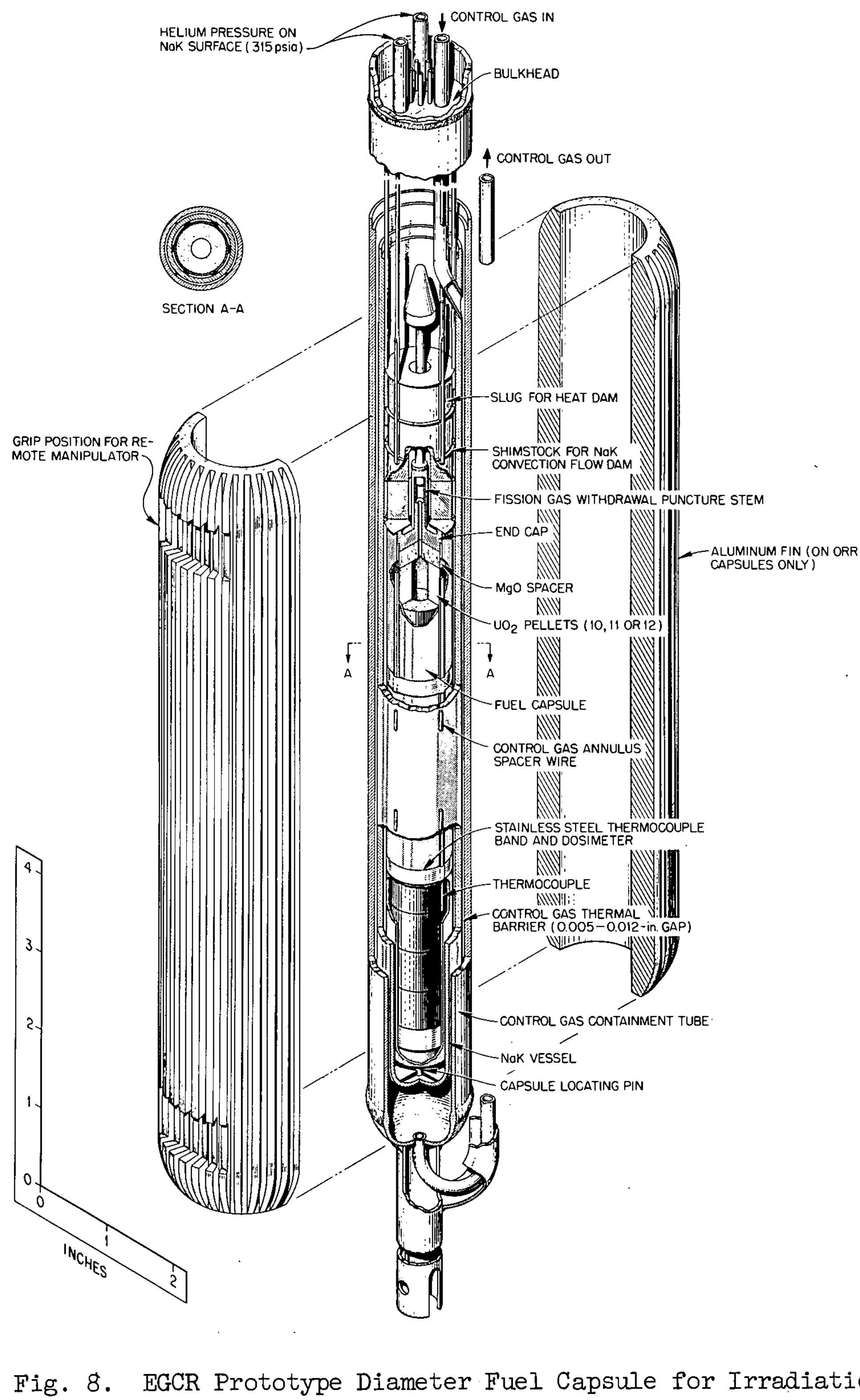

Fig. 8. EGCR Prototype Diameter Fuel Capsule for Irradiation in ORR and ETR.

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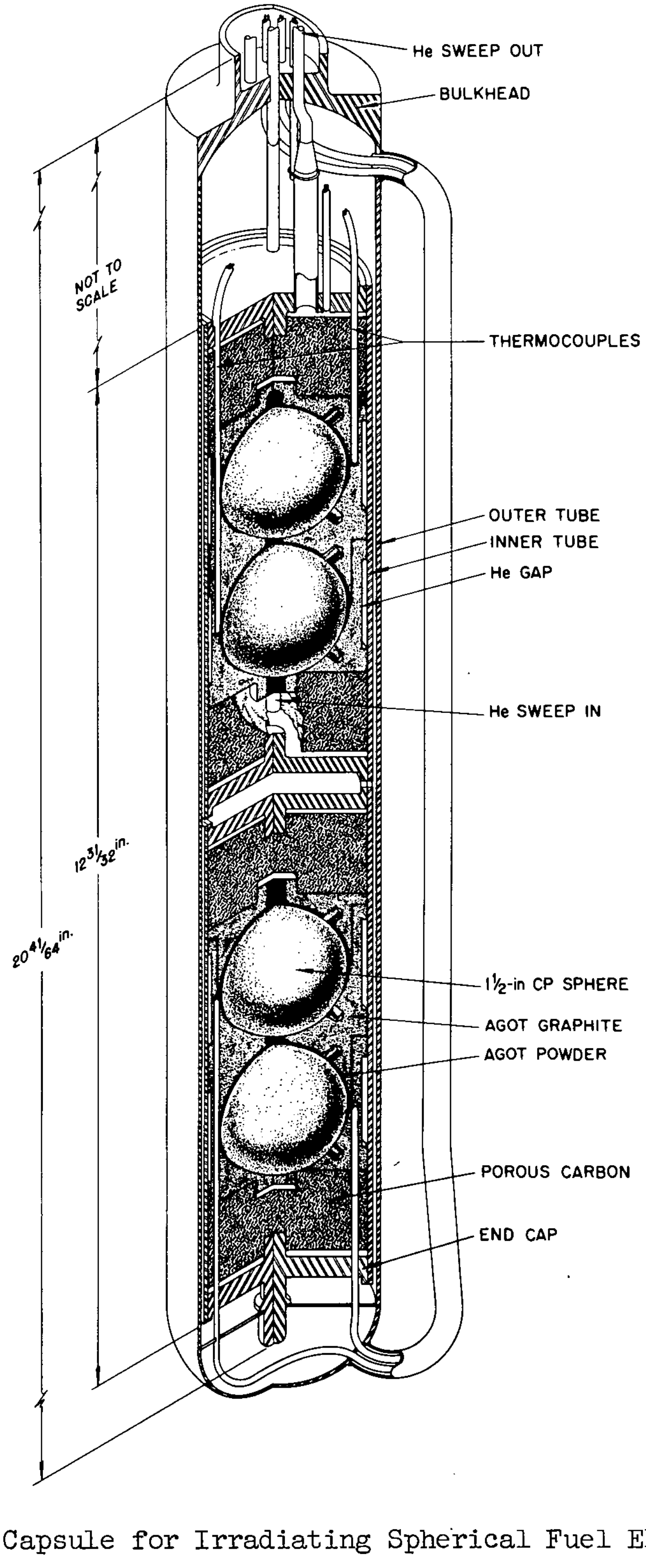

Fig. 9. Capsule for Irradiating Spherical Fuel Elements.

up to 3700°F. It is also possible to measure fuel central temperatures of graphite-matrix pellets and of fueled inserts within spheres at temperatures up to 2500°F. Pressure transducers installed to measure the equilibrium pressure inside clad fuel elements during irradiation have functioned well, but the lifetimes have been limited, possibly by radiation damage to components.

Helium sweep-gas facilities have been provided for either continuous or intermittent determination of fission-gas release. A schematic flow diagram of the sweep capsule control and sampling system is shown in Fig. 10. Gas samples are removed for gamma-ray spectrometer analysis with the equipment shown in Fig. 11. The ratios of gaseous fission-product-release rate to birth rate, R/B, measured to date have varied between 10^{-2} and 10^{-8} for different fuels. Daughter traps that use charged wires to collect solid decay products from noble gases in the sweep circuit, as shown in Fig. 12, provide a means for quantitative measurement of the short half-life noble gases.[20]

The thermal-neutron flux at each station in the irradiation facility can be monitored by argon activation,[21] using the gamma-ray spectrometer for analysis. Movement of the capsules within the flux gradient of the facility can be accomplished during irradiation by means of a gear-driven mechanism operable from the pool surface using tools with extended handles. Manual control has been used with this equipment to maintain nearly constant flux during irradiation, as evidenced by temperature measurements; for example, capsules operated at 1600°F have been held within ±30°F for extended periods.

The test systems described in Table 2 and shown as irradiated in the ORR, except the last one, were tested in this poolside facility. Fifty-six capsules have been irradiated since April 1958. No leakage of fission gases to the reactor room or failure of primary components, except instrumentation, has occurred. The facility has been utilized principally for Gas-Cooled Reactor Program irradiations, but it has flexibility to provide useful test information for many reactor programs. Additional drawings and photographs describing the equipment used are presented in Figs. 13 through 17.

ETR NaK-Cooled Capsules

Equipment installed in the ETR was designed to accommodate 14 capsules simultaneously for comparison of proposed fuel pellets having different configurations for use in the EGCR.[14] The irradiations programmed for these units involved long test periods of up to three and four years, so revisions in equipment have not been necessary, and the present capability is essentially that for EGCR capsules. Very little modification would be necessary to accommodate other capsules; for example, the eight-ball capsule (see next section) could be accommodated by preparation of a new reactor core piece and revision of the lead tubes. By redesign

Table 2. Gas-Cooled Reactor Program Capsule Irradiation Tests, July 1958 Through September 1963

Reactor Application	Test Reactor	Test Item	Cladding Test Condition		Number of Tests
			Temperature (°F)	Pressure (psia)	
EGCR	ETR, ORR	Short, prototype-diameter, stainless steel-clad, UO_2 elements	1500 1300	300 300	18 15
EGCR	ORR	Short, EGCR prototype, instrumented fuel assembly	1500	300	7
EGCR	ORR	Vendor fuel for EGCR	1500	300	5
EGCR	ORR	Vendor fuel for EGCR	1300	300	1
EGCR	LITR[a]	Miniaturized pellets; fission-gas-release tests	1300		27
EGCR	LITR[a]	Capsule instrumentation development	1300		1
AGCR	LITR[a]	$BeO-UO_2-ThO_2$	1300		2
AGCR	LITR[a]	$BeO-UO_2$	1300		3
AGCR	LITR[a]	High-temperature UO_2	4000[b]		4
AGCR-AGR	ORR	Be-clad UO_2 (two capsules by UKAEA)	1100	300	3
AGCR-EL4	ORR	Be-clad UO_2 (four capsules by CEA)	1100	300, 450, and 725	5
AGCR-EL4	ORR	Thin, stainless steel-clad UO_2 (capsules by CEA)	1200	850	2
AGCR	ORR	Swaged stainless steel-clad UO_2	1300	300	3
AGCR	ORR	Tamp-packed UO_2 in stainless steel	1300	300	1
AGCR	ORR	Vibratory-packed UO_2-ThO_2 in stainless steel	1000 and 1300	300	2
AGCR	ORR[c]	$BeO-UO_2$	2100[b]		1
Fueled graphite	ORR[c]	Pyrolytic-carbon-coated UC_2 particles in graphite matrix	1700 and 2400[b]		3
Fueled graphite	LITR[a]	Pyrolytic-carbon-coated UC_2 particles	1300		7
Fueled graphite	LITR[a]	UC fuel	1300		3
Fueled graphite	ORR[c,d]	Pyrolytic-carbon-coated UC_2 particles in graphite sphere	1500		1
Fueled graphite	ORR[c,d]	Fueled matrix insert in graphite sphere	1200		1
Fueled graphite	ORR[c]	Pyrolytic-carbon-coated UC_2 particles in 6-cm-diam graphite sphere with a molded shell	1600		3
Fueled graphite	ORR	Eight-ball test of manufacturing variables and mechanical stability	1500		2

[a]Each LITR capsule had two separate compartments containing like fuel.

[b]Temperature measurement at fuel centerline.

[c]Sweep-type capsules with provision for gas sampling.

[d]ORR capsules for irradiation of graphite spheres had two separate compartments, each containing two similar fuel balls of variable manufacture.

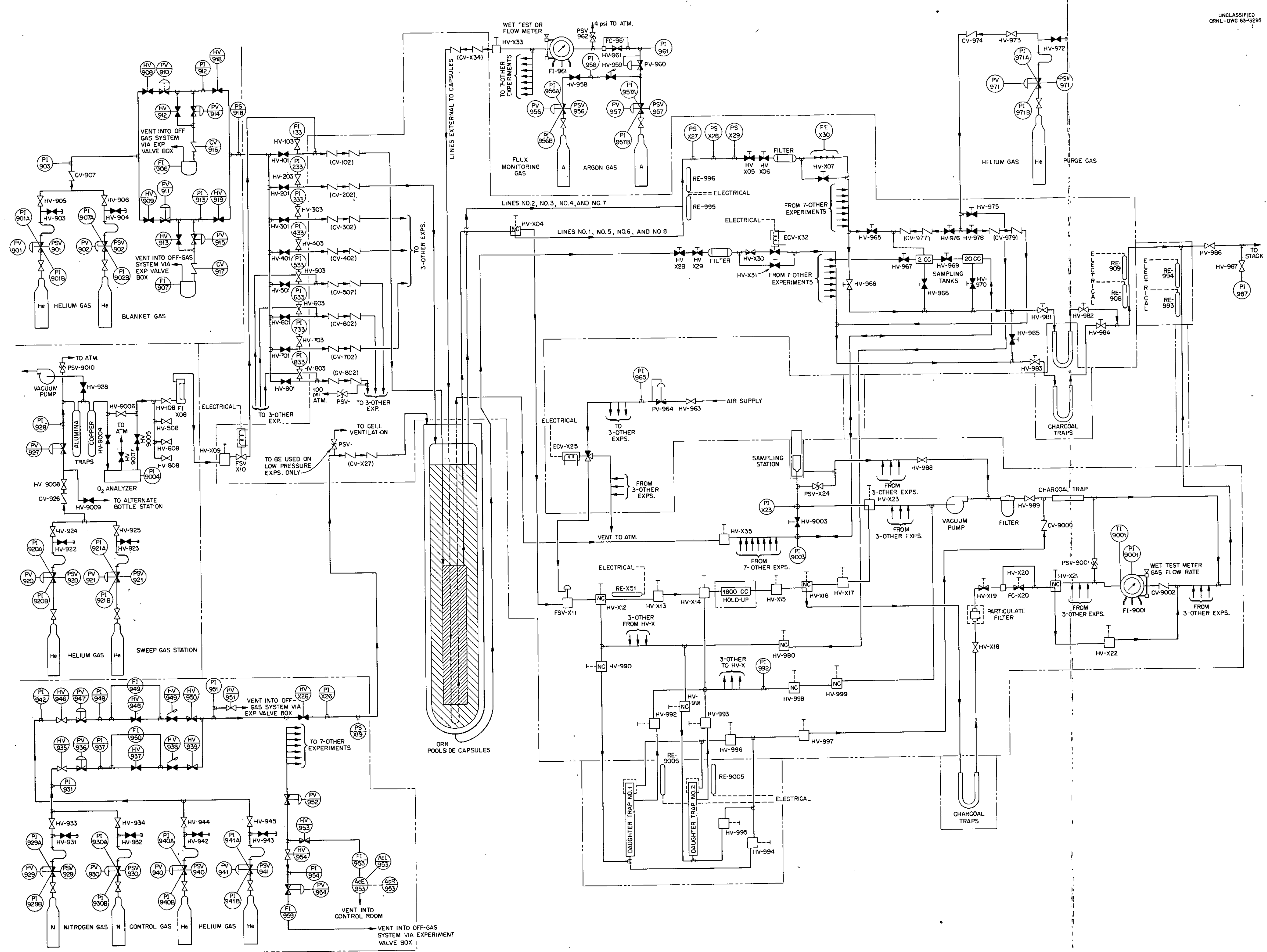

Fig. 10. ORR Poolside Capsule Gas Control and Sampling Systems for Fuel Irradiations.

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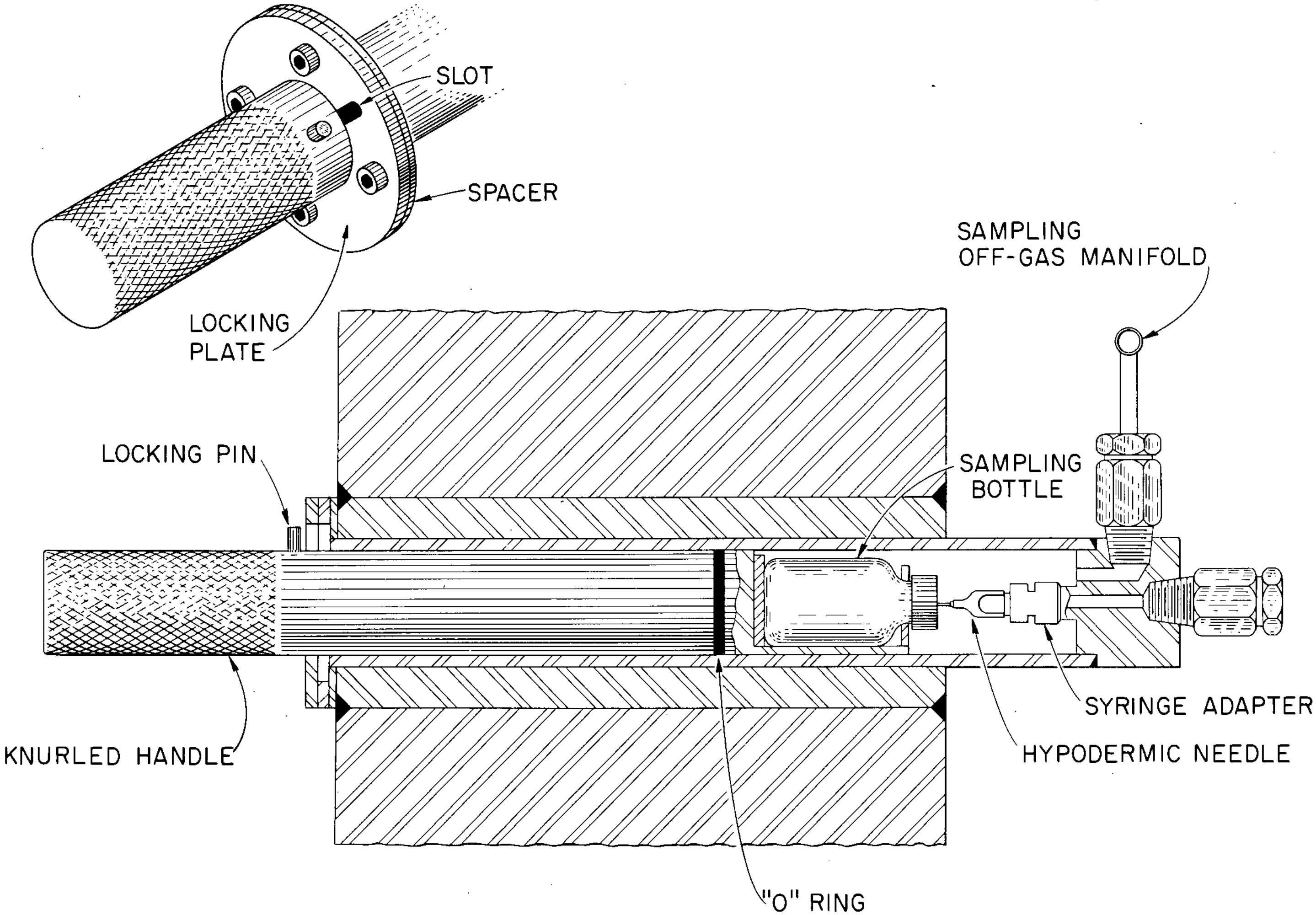

Fig. 11. Sweep Capsule Sampling Station.

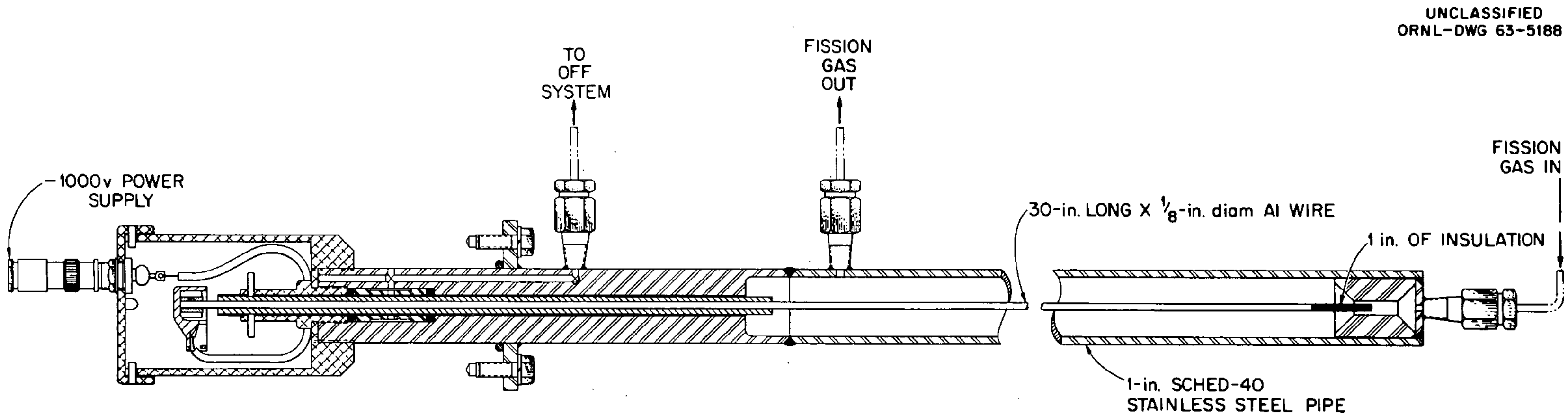

Fig. 12. Daughter-Trap Sampling Wire and Housing for ORR Poolside Capsules.

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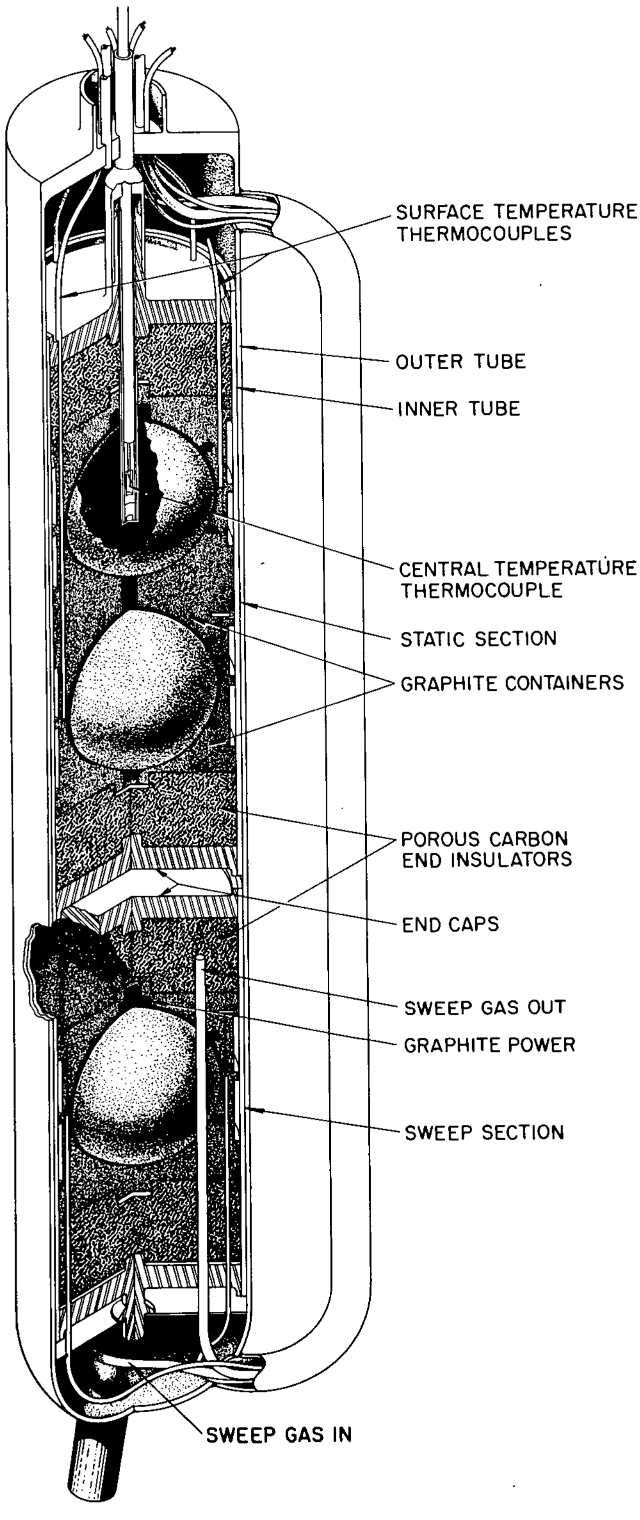

Fig. 13. Sweep Capsule Assembly for Irradiation of 6-cm-diam Spherical Fuel Elements in the ORR Poolside Facility.

Fig. 14. Graphite Parts and Fueled Spheres for ORR Poolside Capsule.

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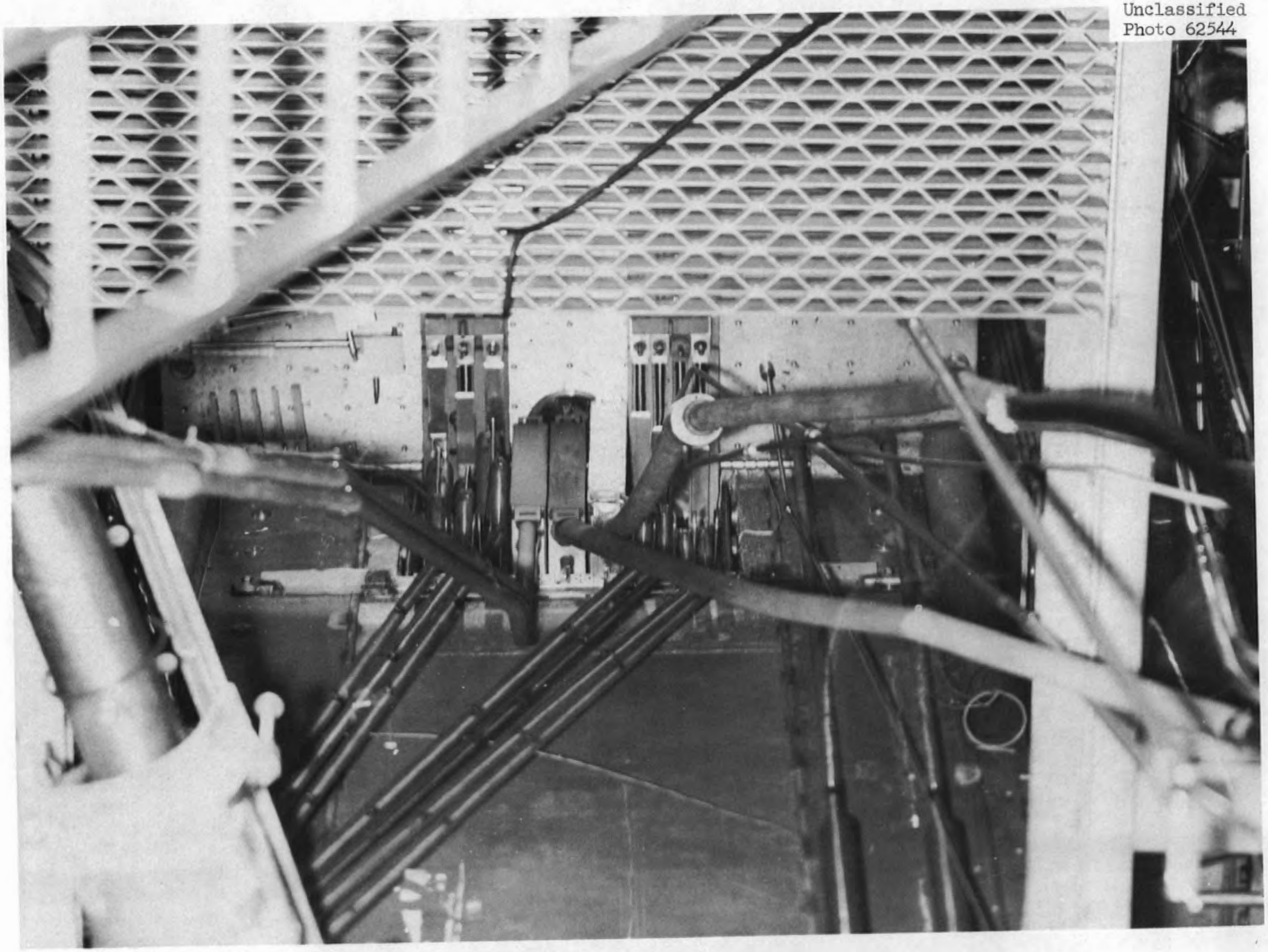

Fig. 15. Closeup Underwater View of ORR Poolside Capsules. Three rectangular boxes at center are for other experiments.

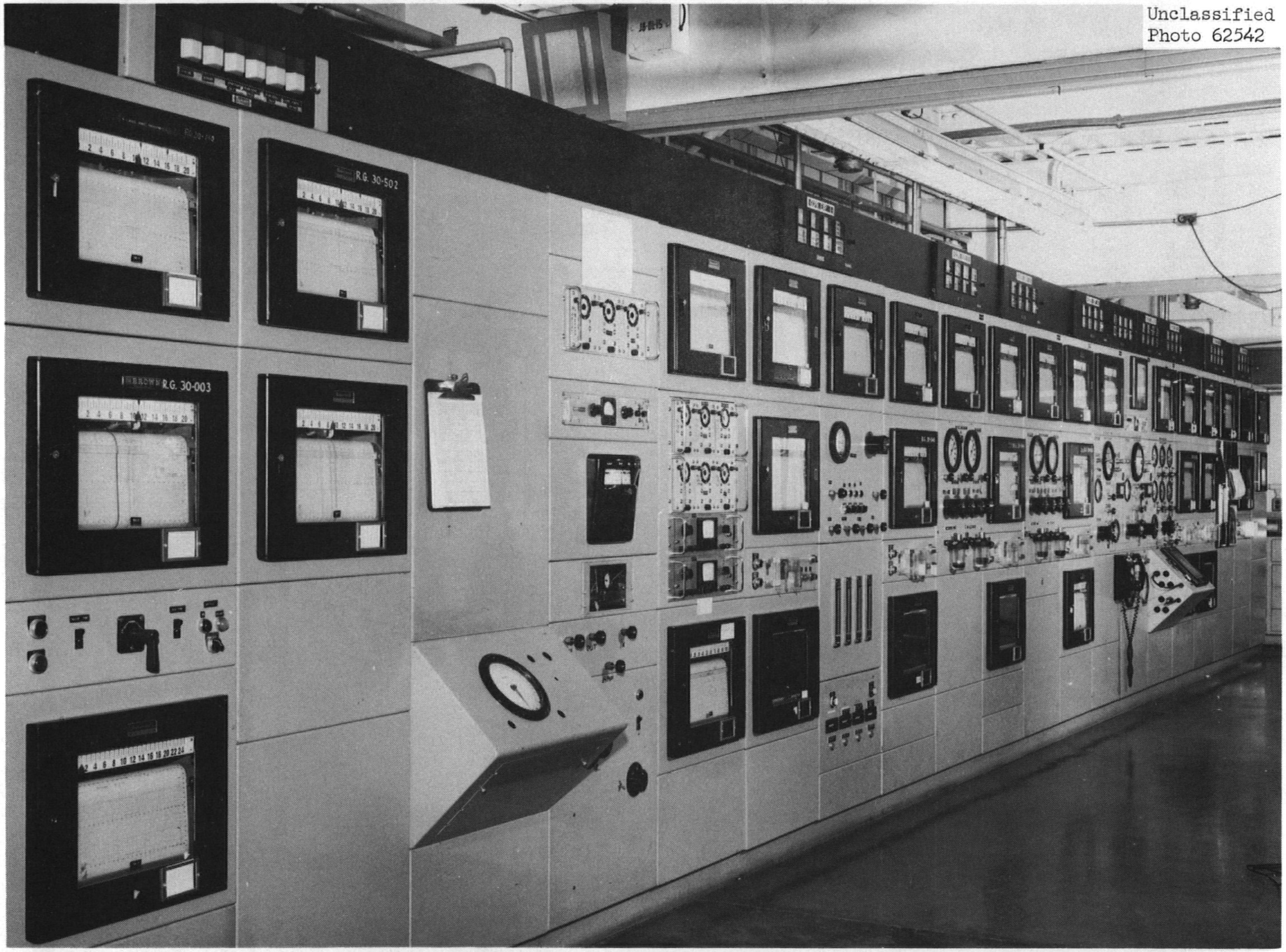

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Fig. 16. Instrument Control Panel for ORR Poolside and Eight-Ball Experiments.

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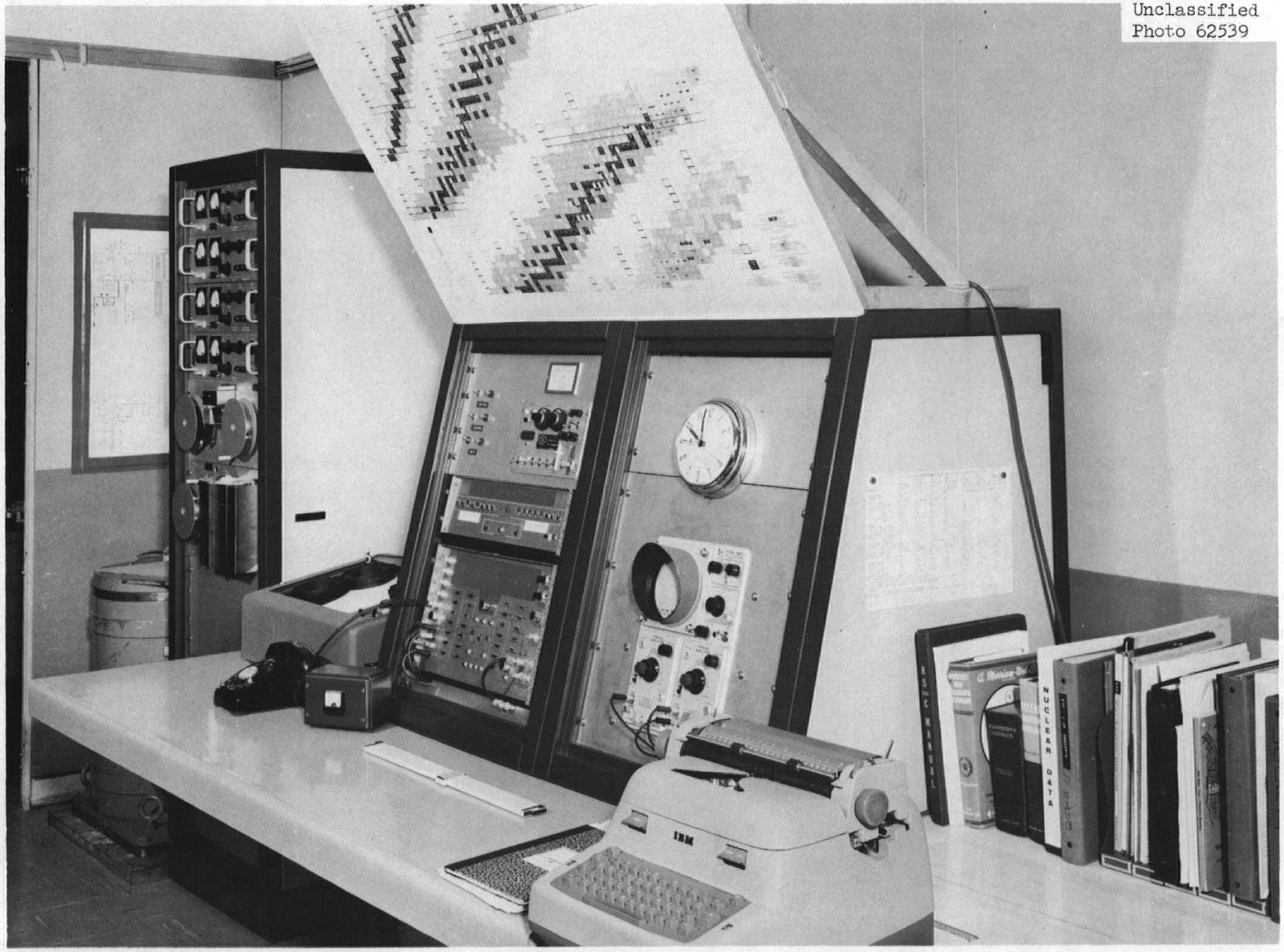

Fig. 17. Gamma-Ray Spectrometer for Loop and Capsule Experiments. Installation for analysis of fission products, argon activation, and corrosion products as applicable to ORR poolside and eight-ball capsules, ORR loop No. 1, ORR loop No. 2, and pressurized-water loop.

for the use of core positions instead of the reflector locations now occupied, the high fluxes for both fast and thermal neutrons of the ETR could be utilized. In particular, tests of sodium-cooled or gas-cooled fast-reactor fuels could be accomplished with very little alteration.

The capsule used is shown in Fig. 8, and the tests conducted at the ETR are listed in Tables 1 and 2. Work on the ETR capsules for the EGCR irradiation program was conducted jointly with the Phillips Petroleum Company.[22]

ORR Eight-Ball Capsule

A capsule was needed in which several spherical graphite elements containing coated-particle fuels could be irradiated simultaneously under similar conditions for comparative evaluation. The fabrication variables to be studied included (1) methods for preparing fuel particles and their coatings and (2) the type of graphite mix and techniques used in forming matrices and unfueled shells, that is, blending procedures, molding processes, heating rates, final treatment temperatures, and impregnation processes. A relatively high fast-neutron flux was desired to accumulate radiation damage in the graphite comparable to that expected for the fuel lifetime in a power reactor. Important considerations in design were measurement of temperature and simplicity in construction to minimize cost.

The capsule is located in core position F-1 of the ORR, which has the advantages of a relatively high fast-neutron flux, 1.3×10^{14} neutrons/cm^2·sec, a uniform thermal flux over a considerable vertical length (peak value, 1.5×10^{14} neutrons/cm^2·sec), and adequate cooling capacity for the spherical elements in a compact arrangement. The facility affords sufficient space to accommodate 1 1/2-in.-diam fuel elements. Based on this diameter and the ORR vertical flux profile, it was determined that suitable irradiation conditions could be achieved for eight spheres — hence, the title eight-ball.

The basic configuration chosen for the experimental assembly is shown in Figs. 18 and 19. The graphite parts are carefully machined and close fitting. Small spheroidal coke particles are used in a loose bed to enhance the heat transfer from the fuel spheres to the graphite structure without restraint on the surfaces of the spheres. The fuel spheres are centered in the cavities by small pins inserted in the graphite. Temperatures are measured by thermocouples inserted in the graphite structure and, when appropriate, inside the fuel spheres. A thermocouple can be installed conveniently in the top fuel sphere. Although the capsule was designed for spherical fuel elements, it could easily be redesigned for other configurations.

The gas gap between the graphite sleeve and the inner wall of the primary stainless steel containment vessel determines the operating

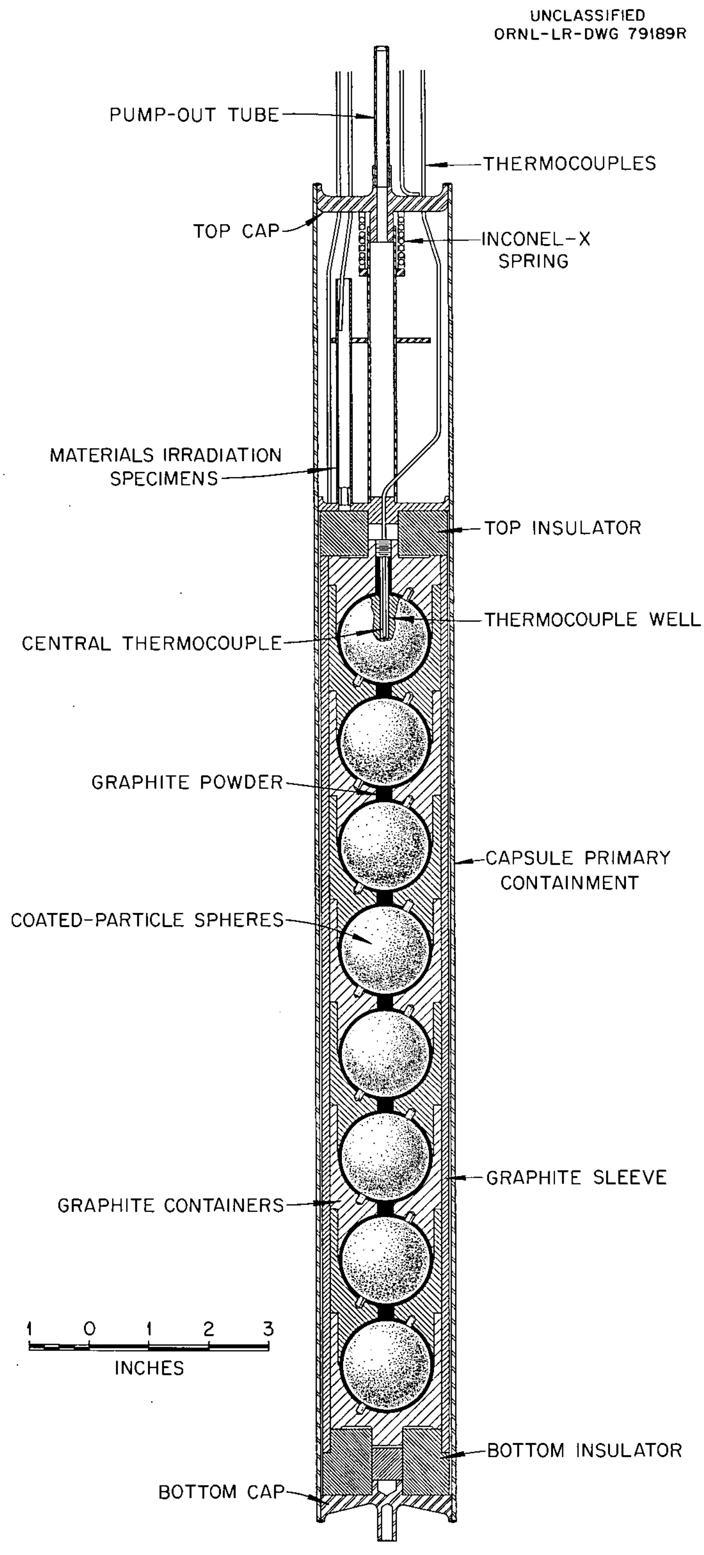

Fig. 18. ORR Eight-Ball Assembly Showing Fueled Spheres Assembled in a Graphite Structure. Secondary outer containment is not shown.

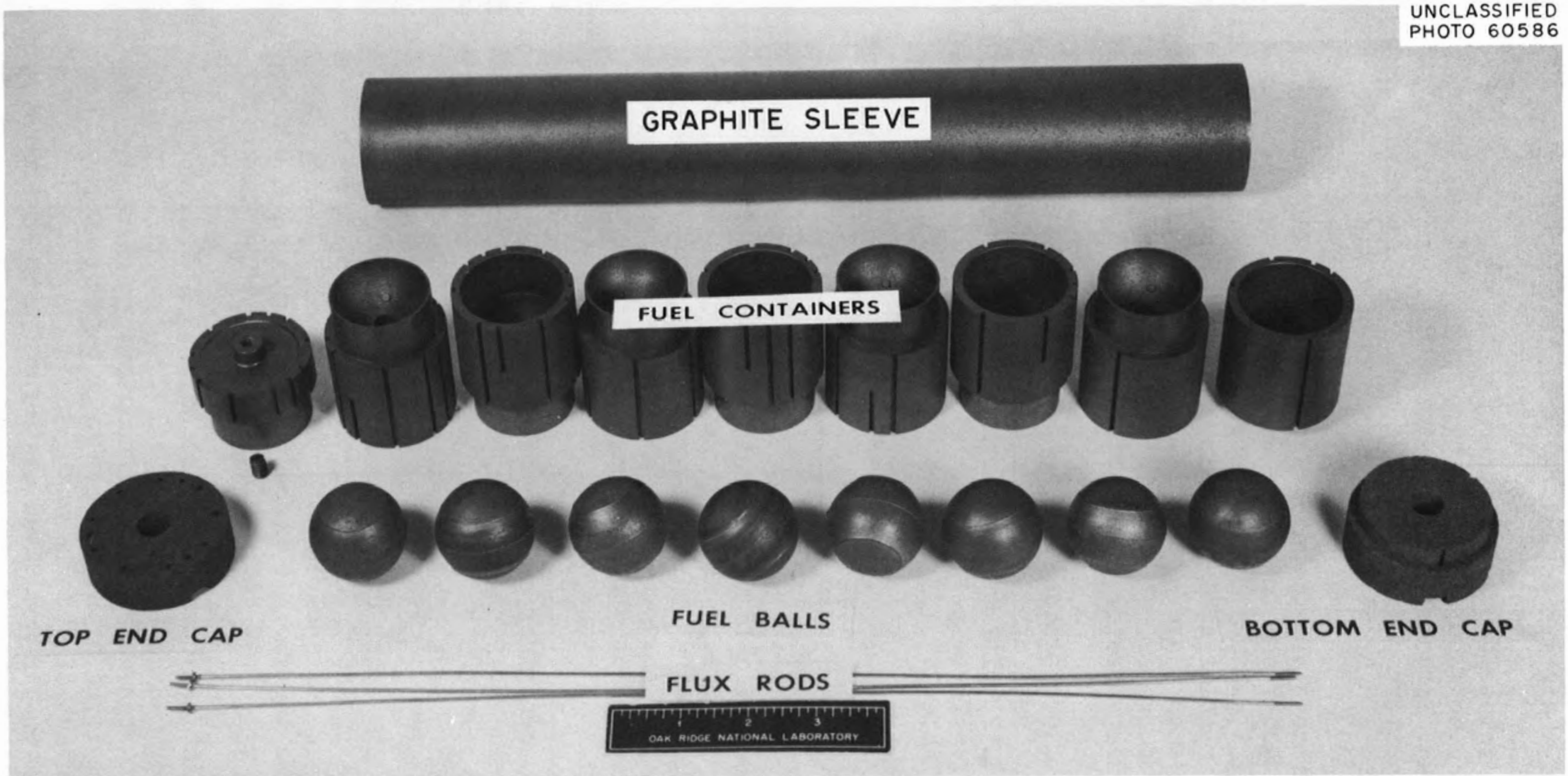

Fig. 19. Eight-Ball Capsule Parts.

temperatures of the graphite and the fuel relative to the primary containment structure. A second gas gap between the primary container and a secondary stainless steel container (not shown in Fig. 18 but arranged similarly to the configuration of the four-ball capsule shown in Fig. 9) was dimensioned to produce a temperature difference of several hundred degrees Fahrenheit when filled with a helium-nitrogen mixture. The gas mixture is varied to provide temperature control.

The experiments are operated from ORR poolside capsule instrument panel position No. 7 and share the same shielded valve-control box, sampling station, and gas supply, as shown in the schematic diagram of Fig. 10; thus all variables achievable in the poolside facility, except neutron flux adjustment, are available. The sharing of facilities provides the advantage of economical operation for this experiment, since very little additional operator coverage is required.

The overall performance of the capsule has been quite satisfactory. Temperatures in the graphite at the midplanes of fuel spheres have varied no more than ±50°F, with an approximately symmetrical pattern about the vertical center. The experiments that have been conducted in this facility are listed in Table 2.

LITR Air-Cooled Capsules

The equipment for LITR irradiations utilizes forced-air cooling of the capsule.[14,15] Two of the designs employed are shown in Fig. 20. One assembly accommodates a small specimen of solid fuel, such as UO_2, UC, or UN, which may be surrounded by a ceramic insulating sleeve to obtain higher temperatures, as shown in the parts display of Fig. 21. A third design provides small cans of noble or refractory metal to contain coated particle or granular fuels[23] (shown in Fig. 22). A gas annulus between the fuel or its container and the outer wall of the capsule permits operation at considerably higher temperatures than are possible for the capsule container. Two or more separately enclosed fuel containers can be accommodated in each half of the capsule. Containers made of graphite or of ceramics can be used where metals are not compatible with the fuels to be tested. The outer container for these capsules is designed only for convenience of the fuel irradiation, with no attempt to obtain information relative to encapsulation techniques. Figures 23 and 24, respectively, show the facility tube that directs the air flow over the capsules and a schematic diagram of the system and controls.

An important and common feature of most LITR capsule designs is the thermocouple for measuring the central temperature of the hollow fuel specimens. Tungsten vs rhenium or tungsten vs rhenium alloy thermocouples are normally employed with tantalum or a refractory metal sheath to prevent direct contact of the thermocouple junction with the fuel. Irradiations of UO_2 have been conducted at temperatures giving an indicated output of 37 mv with W–5% Re vs W–25% Re thermocouples. The temperature

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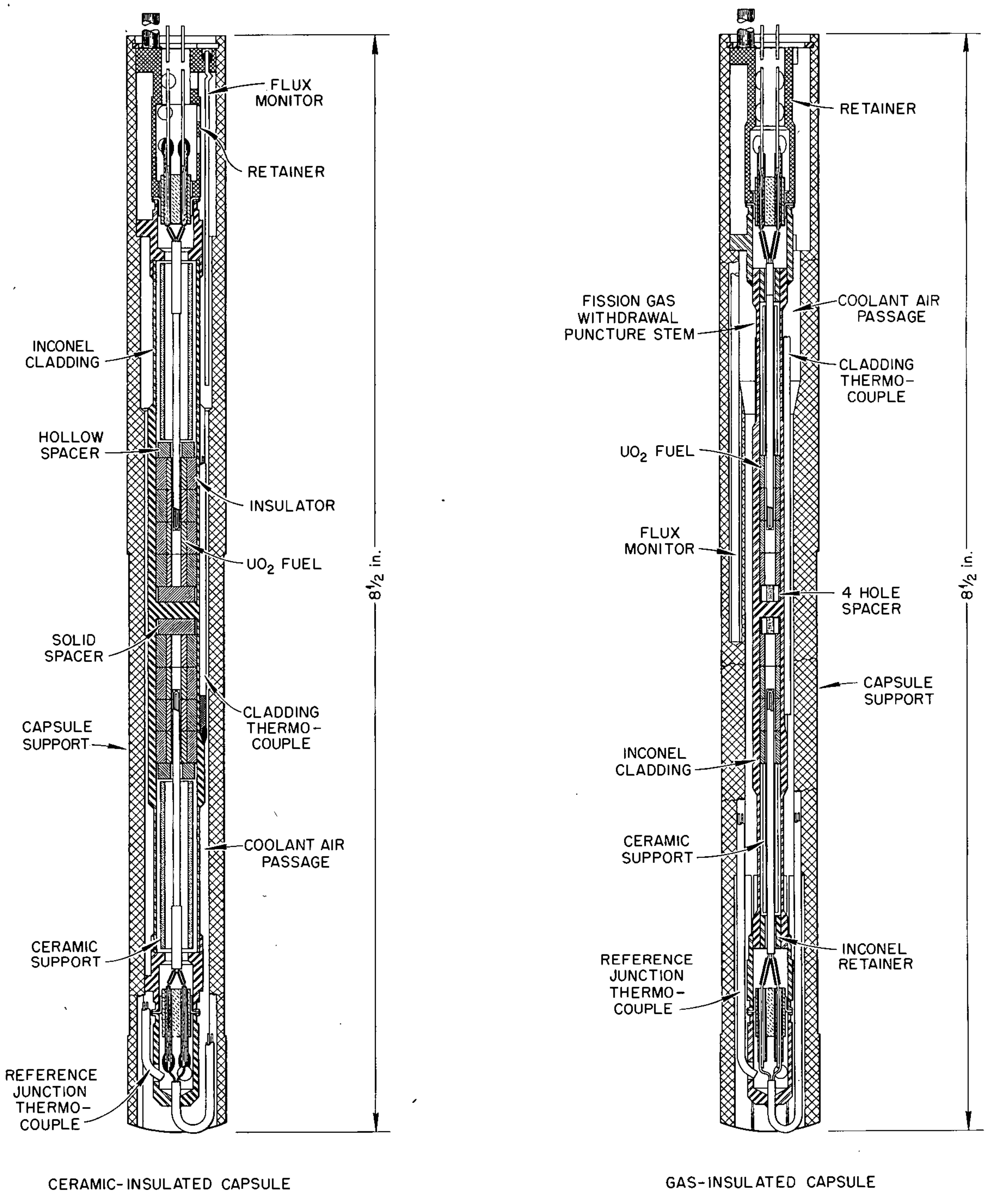

Fig. 20. LITR Capsule Parts.

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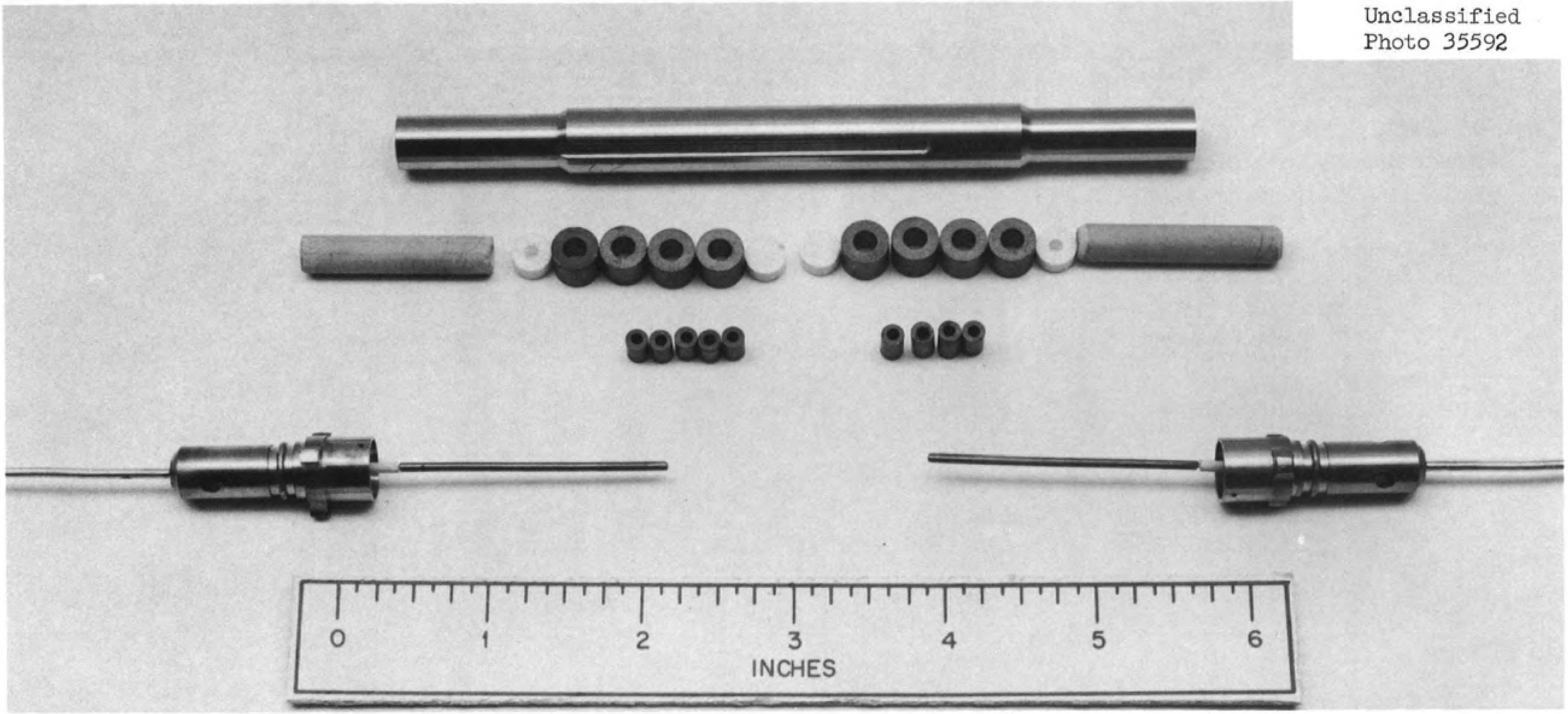

Fig. 21. LITR Capsule Parts Prior to Assembly. Thermocouples, hollow cylindrical fuel pellets, ceramic insulators, and the capsule container, respectively, are shown from bottom to top.

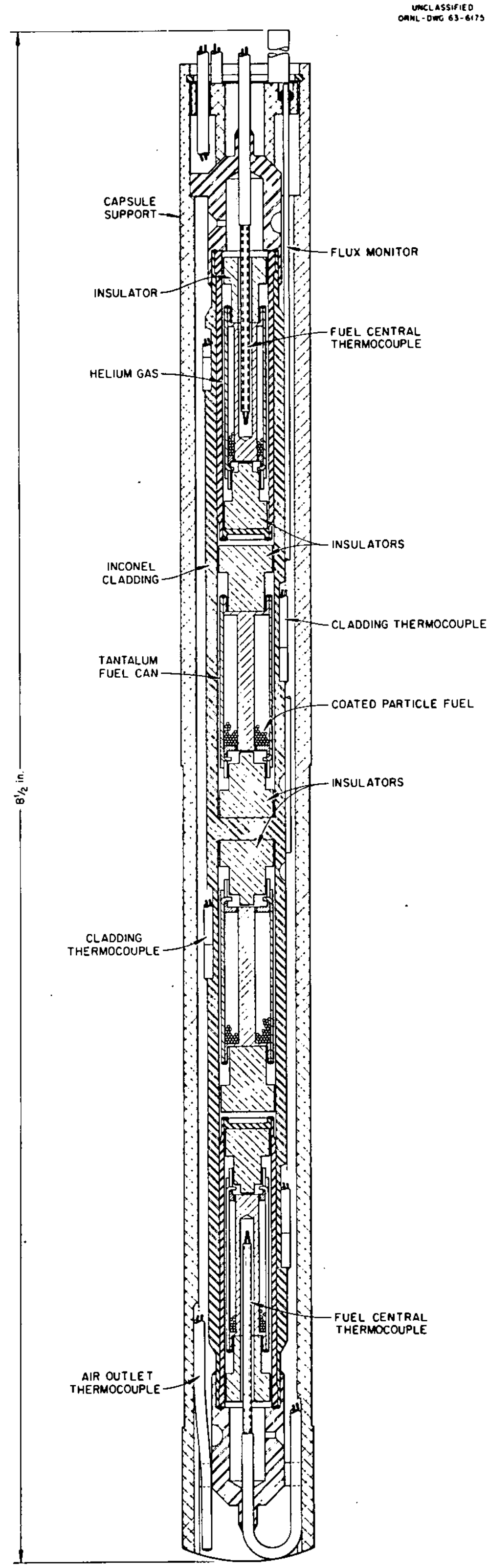

Fig. 22. LITR Capsule for Irradiating Coated Particle Fuel.

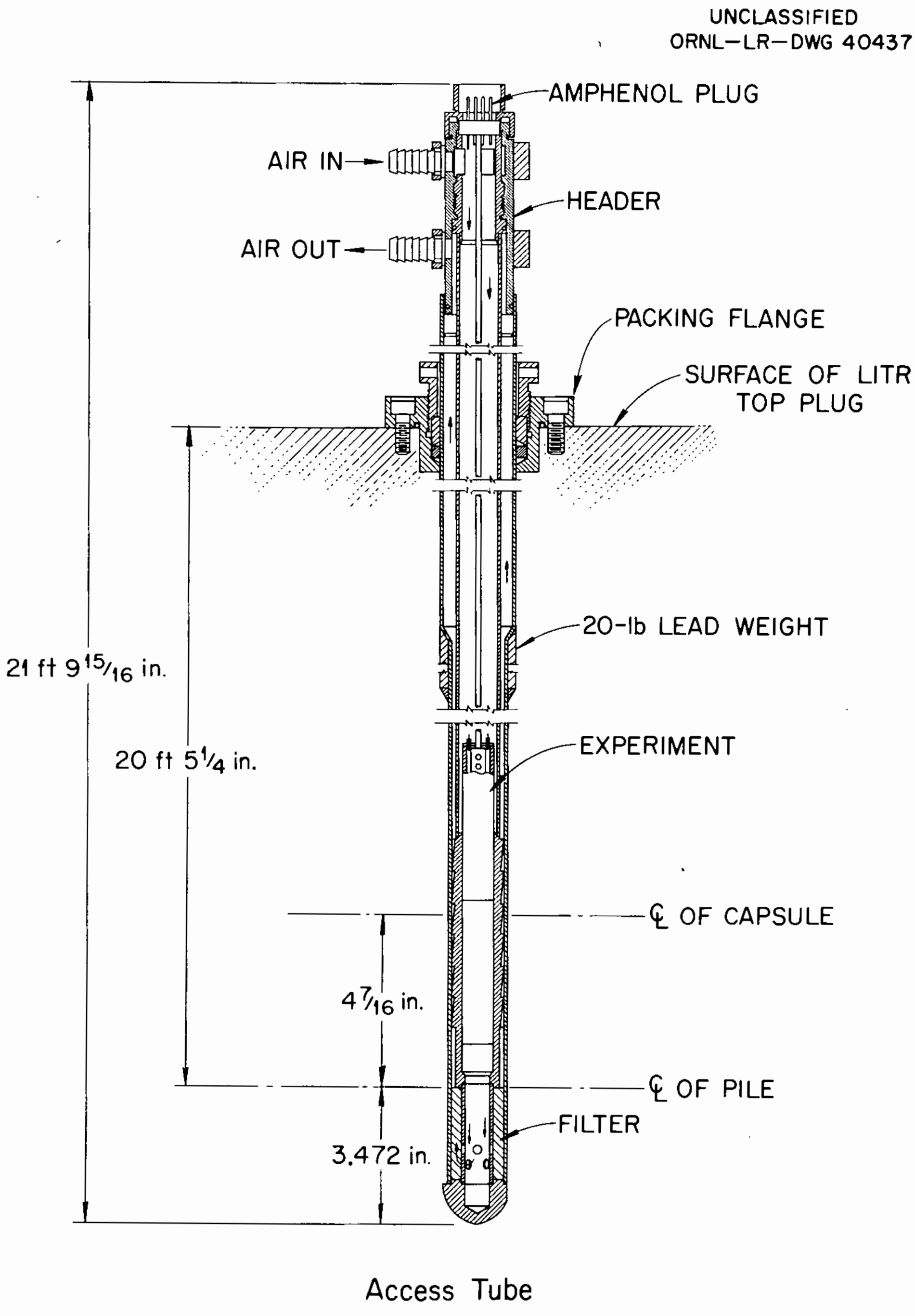

Fig. 23. LITR Capsule Access Tube to Direct Cooling Air Over Capsule and Isolate It from the Reactor.

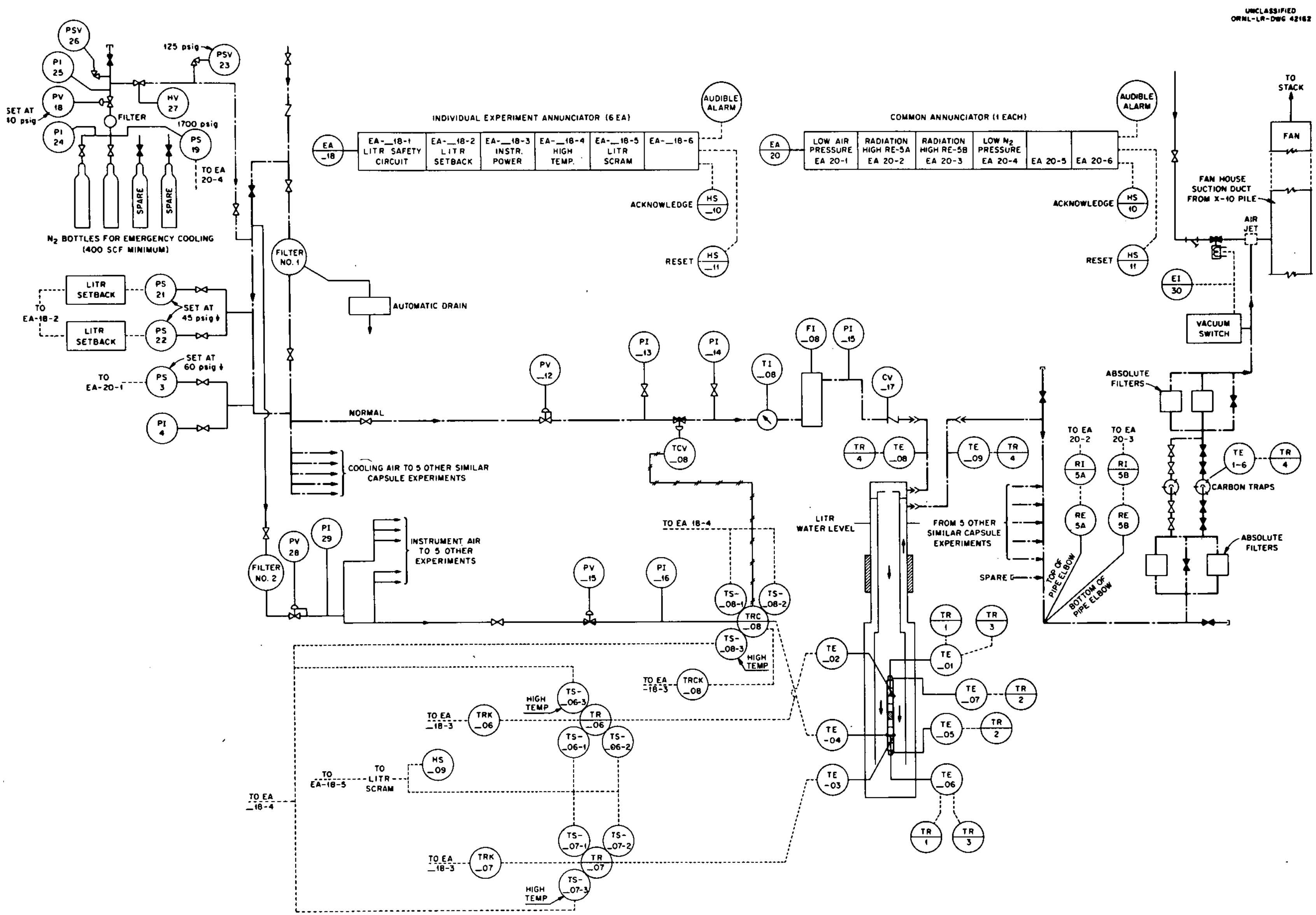

Fig. 24. Flow Diagram for LITR-GCR Experiments.

corresponding to this emf, as obtained by extrapolation of a calibration curve above its 4200°F limit,[24] is approximately 4400°F. At these temperatures, a rapid downward drift in emf occurs early in the irradiation period, but the cause cannot be determined precisely from these experiments. Changes in the fuel structure and thermal conductivity could be contributing factors, as well as thermocouple instability and insulation breakdown. Below 3200°F, the indicated temperatures are consistently quite stable, and stable operation is also observed in some instances at higher temperatures. Closure of the capsule is achieved with a commercially available metal-to-ceramic hermetic insulating seal through which the thermocouple lead wires pass.

Control is based on temperatures measured on the lower capsule wall, which operates at the higher equilibrium temperature, and is effected by varying the air velocity and corresponding heat transfer coefficient. Measurements of the air flow and its temperature above and below the capsule provide for determination of the total power generation.

These capsules have the advantage of simplicity and economy in construction. The small size permits operation at very high power densities, and thus high burnup is achieved in relatively short exposure times. The capsule control is automatic and requires little operator attention. Seven double capsules can be operated simultaneously with equipment presently available at the LITR. The thermal-neutron flux in the assigned LITR core position (shown in Fig. 2) varies between 5×10^{12} and 2×10^{13} neutrons/cm^2·sec; other capabilities are given in Table 1. Irradiations conducted in LITR capsules are listed in Table 2.

ORR Gas-Cooled Loop No. 1

Gas-cooled loop No. 1,[25] which is equipped to recirculate helium gas, was designed to test clad fuel elements appropriate to the EGCR or similar reactors of more advanced concept.[26] It also is quite suitable for tests of fuel elements for fast gas-cooled reactors. The overall capability of the loop is described in Table 3. Although designed for operation with helium, the loop can be used with several gas coolants. The principal components and their location in the ORR facility are shown in Fig. 25. Most of the loop is located within the ORR pool to utilize the shielding afforded by the water. The compressors, primary instrumentation, and some auxiliary equipment are located in a shielded cubicle on the lower balcony to provide access for maintenance.

The interrelationships of the main loop components are shown in the schematic flow diagram of Fig. 26. Helium coolant at flow rates up to 400 lb/hr is circulated through the loop at a nominal pressure of 300 psia by two turbine compressors, of the type shown in Fig. 27, piped in series. A typical loop temperature profile for operation with a fuel element having a heat rating of 35,000 Btu/hr·ft is shown in Fig. 28. The maximum allowable temperatures at critical points are 1400°F for

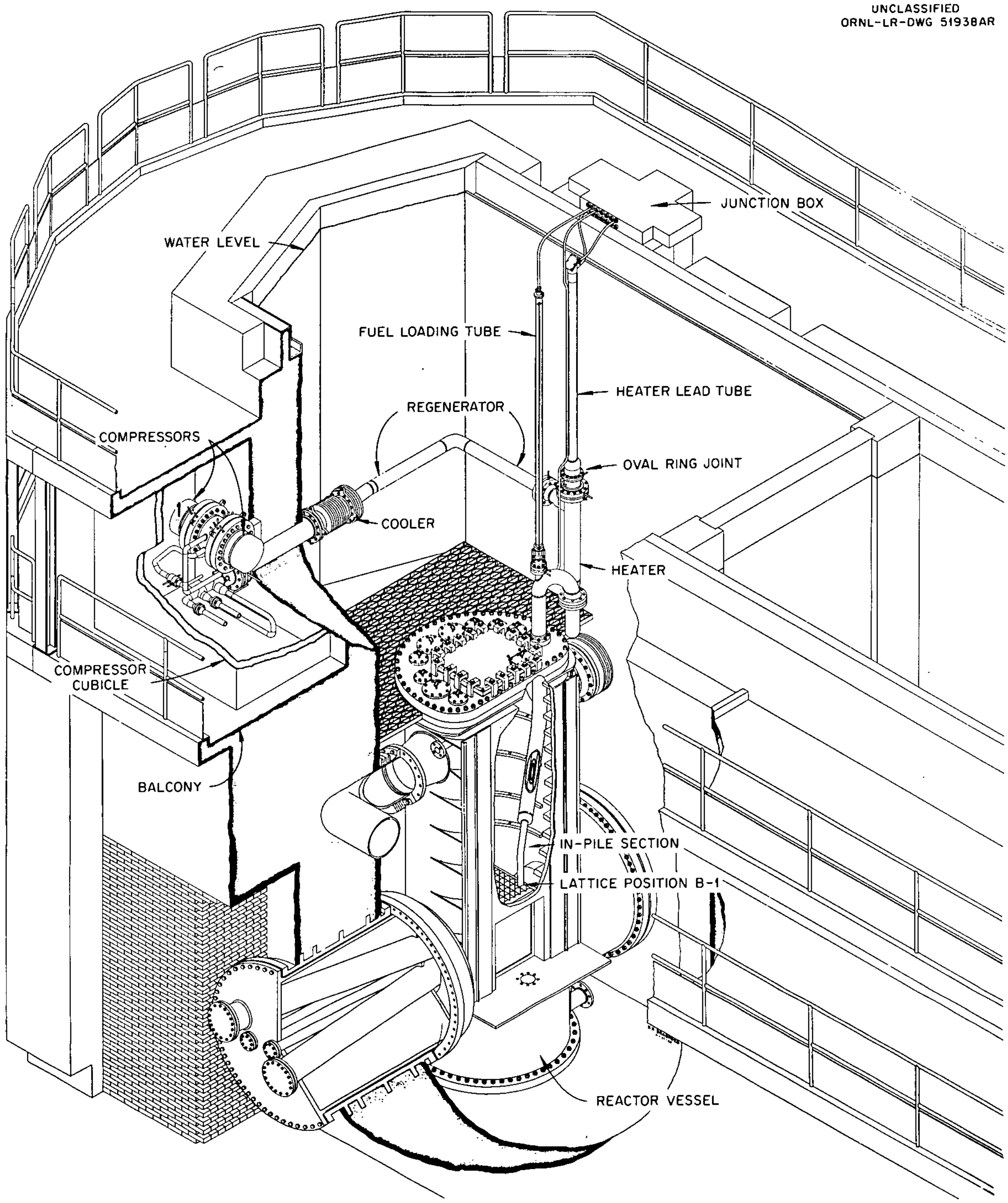

Fig. 25. GCR-ORR Loop No. 1 Principal Components and Their Relationship to the ORR Facility.

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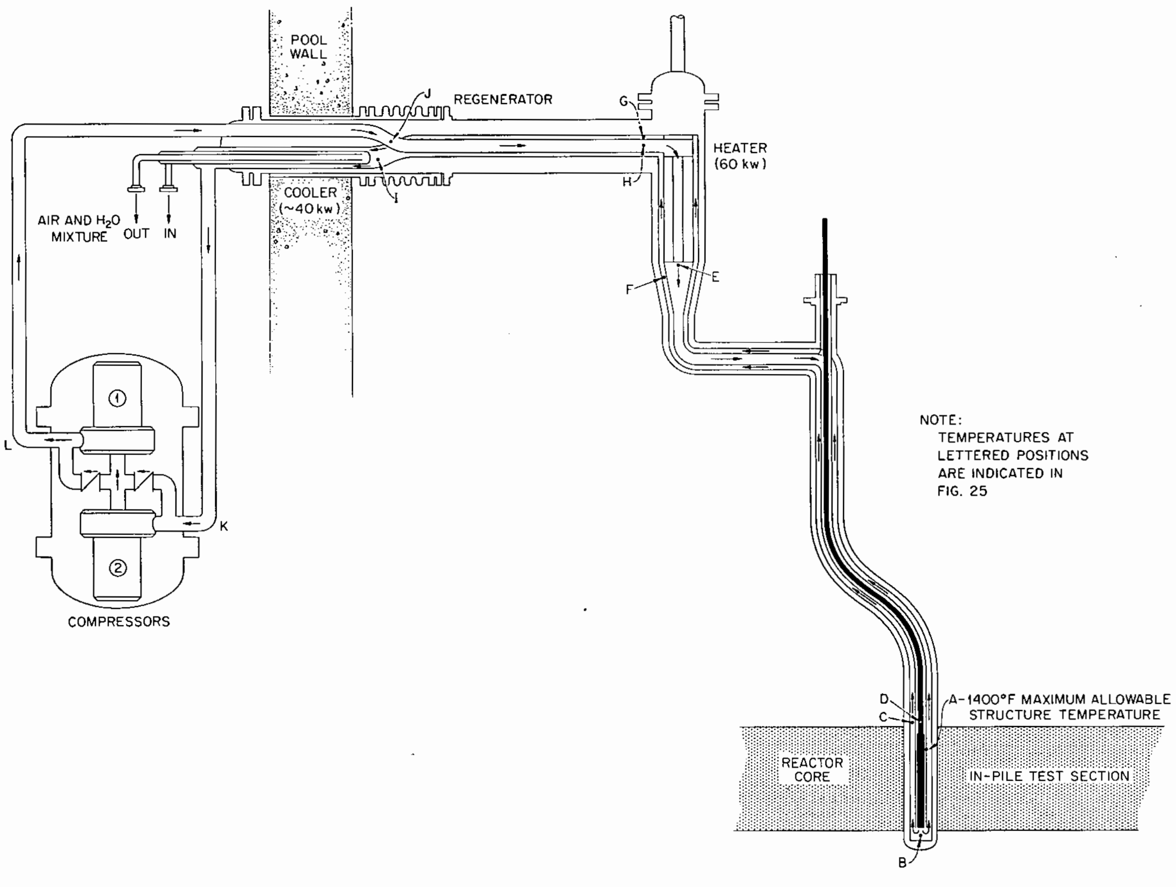

Fig. 26. GCR-ORR Loop No. 1 Schematic Flow Diagram.

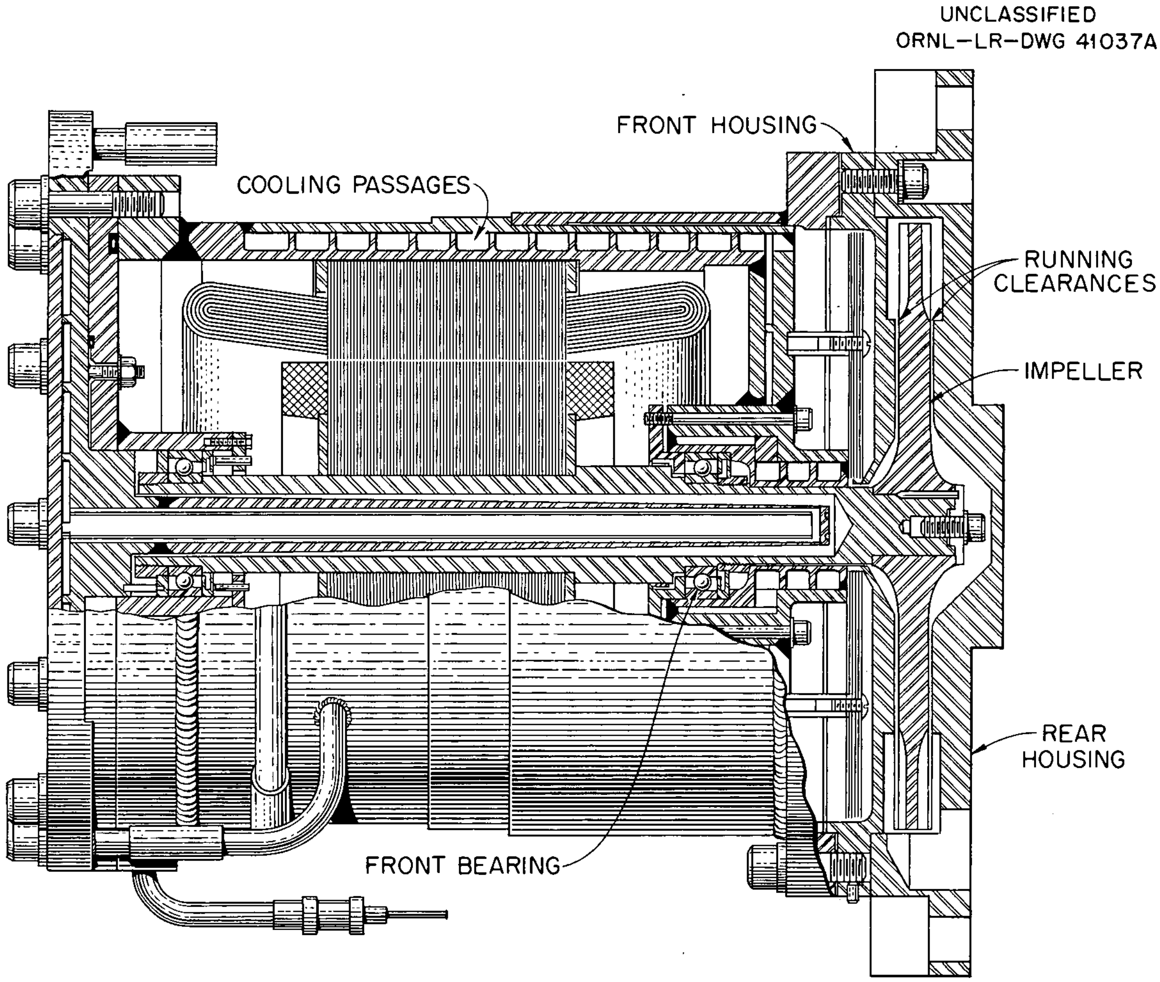

Fig. 27. HECT-II Compressor for GCR-ORR Loop No. 1.

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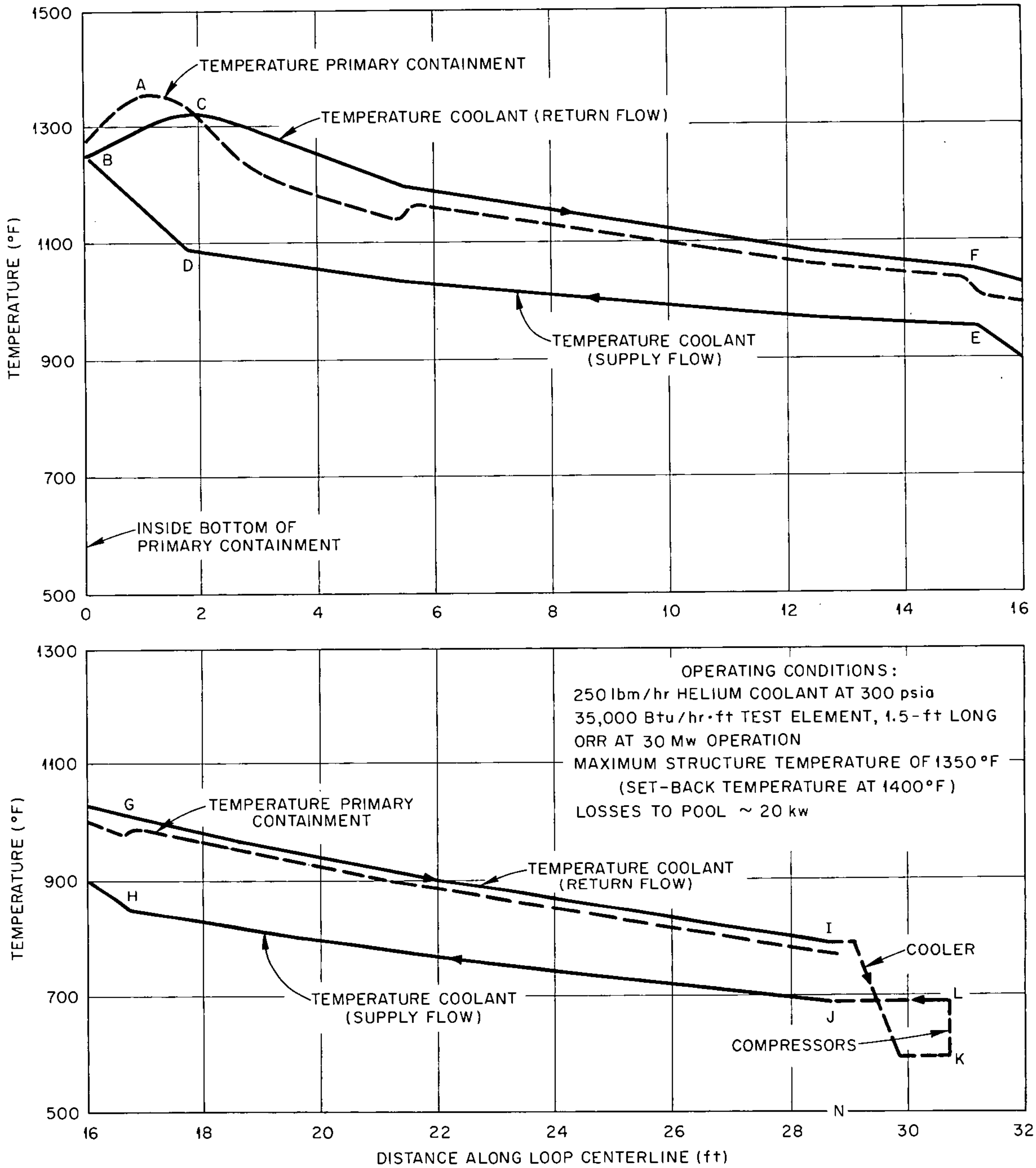

Fig. 28. Typical Temperature Distribution for GCR-ORR Loop No. 1. Letters on curves refer to lettered positions on Fig. 26.

Table 3. Capacity of ORR Gas-Cooled In-Pile Loops

	Loop ORR-1	Loop ORR-2
Primary usage	Testing clad fuel[a]	Testing unclad fuel
Startup date	July 1961	January 1963
Thermal-neutron flux, neutrons/cm^2·sec	5×10^{13}	8×10^{12}
Fast-neutron (>0.1 Mev) flux, neutrons/cm^2·sec	5×10^{13}	4×10^{13}
Specimen size (max), in.		
Outside diameter	1	2.75
Length	19	9
Pressure (helium), psi	300	300
Fuel element temperature (max measured), °F	4000	2500
Coolant exit temperature (max), °F	1400	1500
Coolant inlet temperature (max), °F	1350	1200
Flow rate (max), lb/hr	400	980
Heat removal limit, kw	60	20[b]
Activity limitation, curies	5	100[c]

[a]Loop can also accommodate unclad ceramic, ventilated clad, or metal matrix elements.

[b]Heat generation is limited to 20 kw by present in-pile tube design; the loop has capability for removal of 60 kw.

[c]With revision of equipment for fuel-element removal, operation could be permitted with 1000 curies of mixed fission-product activity in the coolant.

stress limits of the in-pile structure of the primary containment vessel and 600 to 800°F at the compressor inlet, as limited by the turbine wheel design and motor windings. Heat losses to the pool and in the compressor cubicle are made up by a 60-kw heater. Primary heat removal from the loop is accomplished by a bayonet type of cooler utilizing an air and water mixture, with the primary temperature control provided by varying the amount of water introduced into the air. Regenerative heat transfer in the annular piping system is utilized to conserve energy while maintaining the inlet gas temperature to the fuel element as high as 1350°F. The piping is essentially an all-welded system except at the loading station, heater cover, and the cooler bulkhead joint, which are flanged assemblies. The loop is doubly contained in its entirety to permit the testing of fuel elements under severe conditions without hazard. Loop instrumentation provides for continuous monitoring of important variables, including fuel, gas and loop structure temperatures, radiation levels, and all other parameters essential to safe operation. Helium released from the loop through normal venting or by overpressure relief valves passes through water-cooled activated-charcoal traps before being discharged to the ORR offgas system.

Gas-sampling provisions are adequate for determination of both chemical and radioactive noble gas impurities at very low levels. The conduit support for the fuel elements affords considerable surface area to collect fission or gaseous corrosion products and considerable space is available there for insertion of corrosion specimens and other experimental devices.

The loop operates nearly automatically but is manned with technicians to provide close adherence to the design test conditions, to ensure corrective action in the event of trouble, and to compensate for off-design reactor operation resulting from control action by other experiments. During two years of operation, the loop has caused a reactor shutdown on only one occasion. This shutdown was necessitated by serious failure of a fuel element under test. Operation has been continuous throughout all other reactor operating periods.

Details of a typical fuel element for irradiation, equipment for installation and removal of hot elements, and sectional views of the in-pile position of the loop are shown in Figs. 29 through 32. Figure 33 shows the loop and other equipment in the ORR pool, and Fig. 34 shows the instrument control panel.

Recent studies have shown the fast-neutron flux ($E > 0.1$ Mev) to be about 5×10^{13} neutrons/$cm^2 \cdot sec$ in the ORR B-1 core position of loop 1. Thus the facility is of interest for fuel studies of gas-cooled reactors operating in the epithermal flux region. A fuel element test has demonstrated capability of the loop for operation with unclad fuel elements. Approximately 1 curie of noble-gas fission products released from a deliberately vented clad element was circulated in the loop for an extended period.[27] Following this operation, the loop was opened both for changeout of fuel and replacement of both compressors. No spread of contamination was experienced, and the changeout was completed easily within a normal ORR shutdown period.

The fuel test program for the loop has been intensive. During a little more than two years of operation, the loop has irradiated a total of 14 test specimens. With one exception, each test was conducted with quite satisfactory loop operation, although some tests resulted in failure of the specimen. A list of the experiments, their nature, and the operating conditions is given in Table 4.

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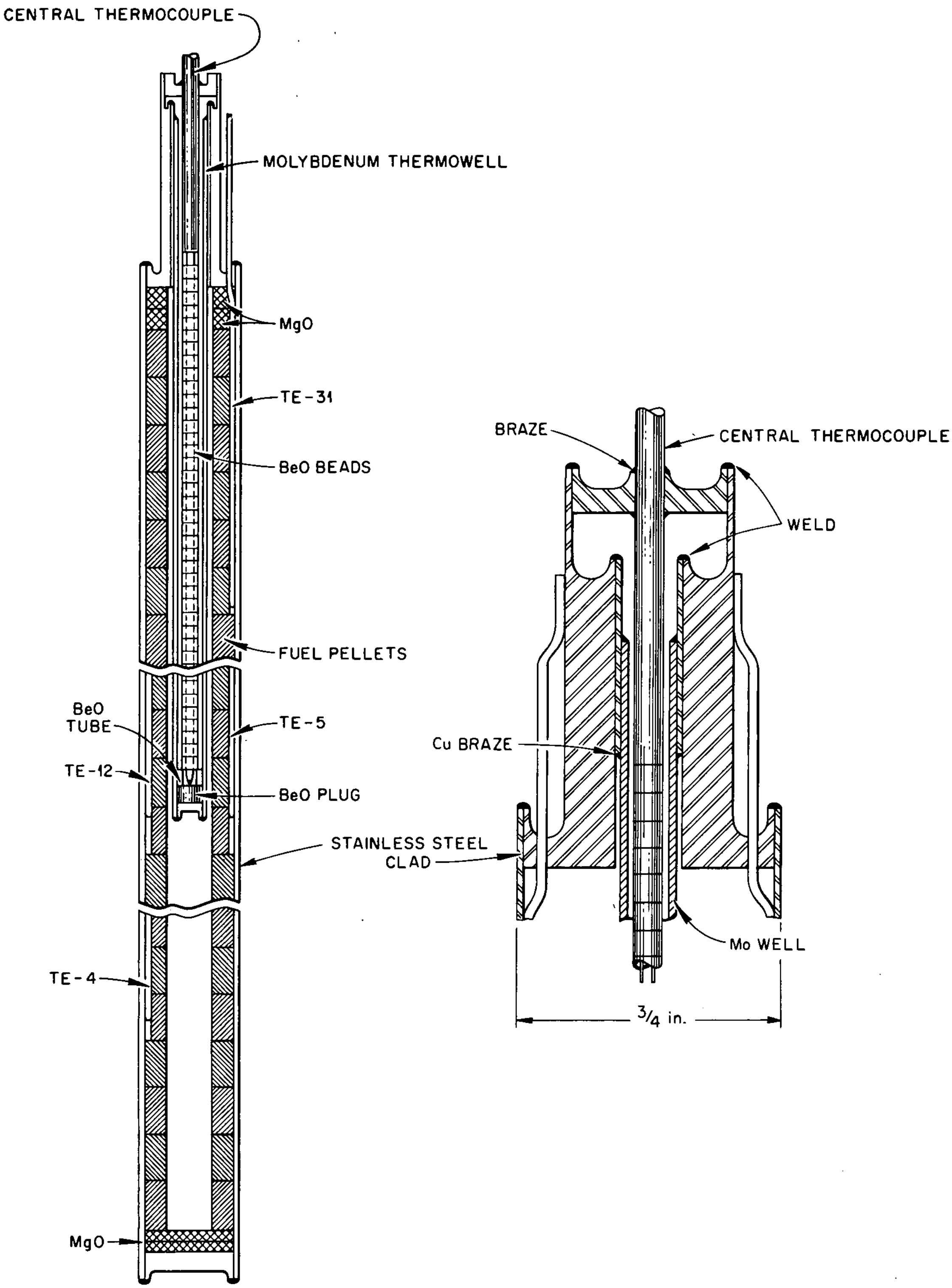

Fig. 29. Typical Test Fuel Element for Helium-Cooled Loop.

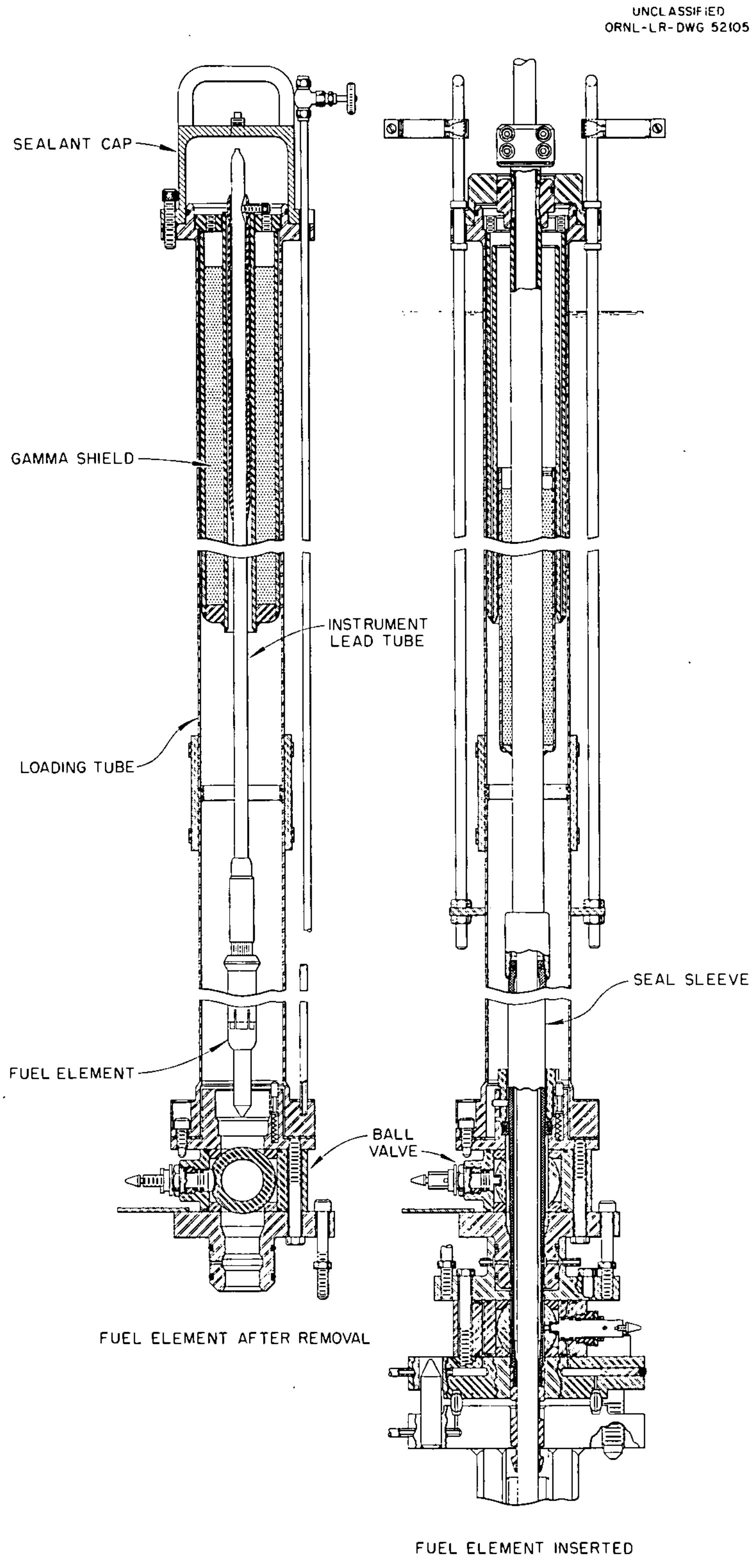

Fig. 30. GCR-ORR Loop No. 1 Loading Station. Irradiated fuel can be removed dry from the loop using ORR pool water for shielding during transfer to the ORR hot cell, where initial dismantling is performed.

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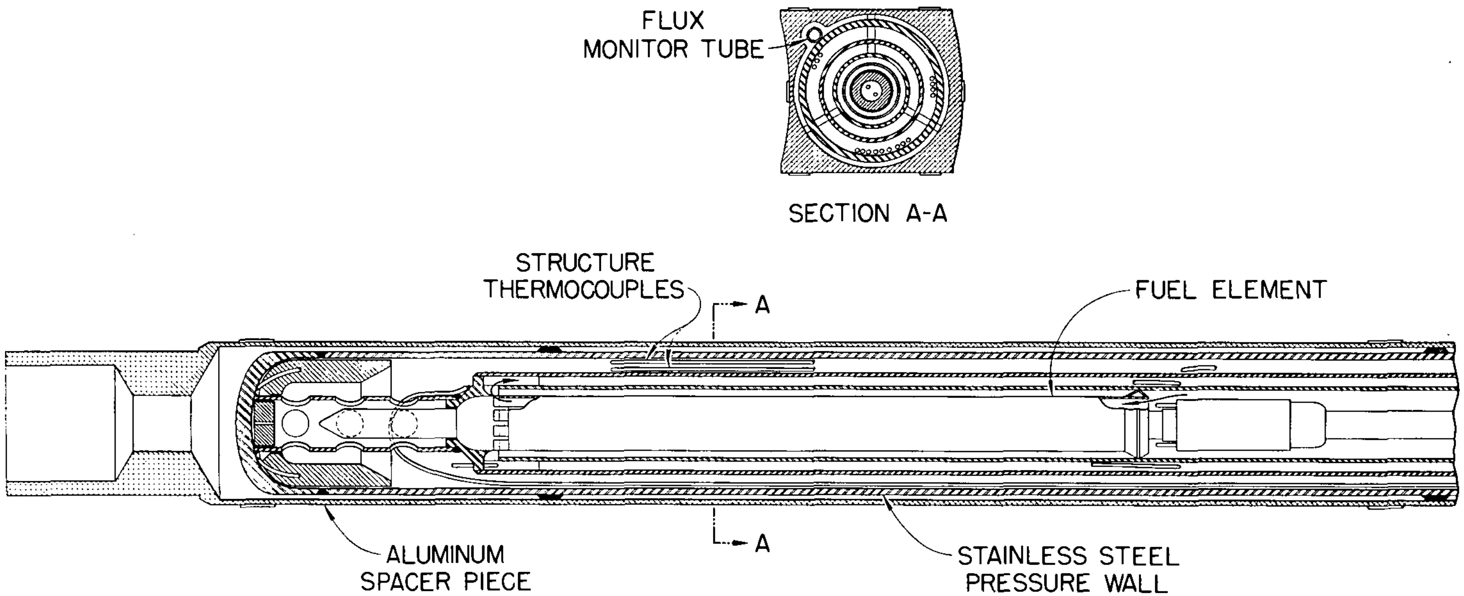

Fig. 31. Loop In-Pile Section.

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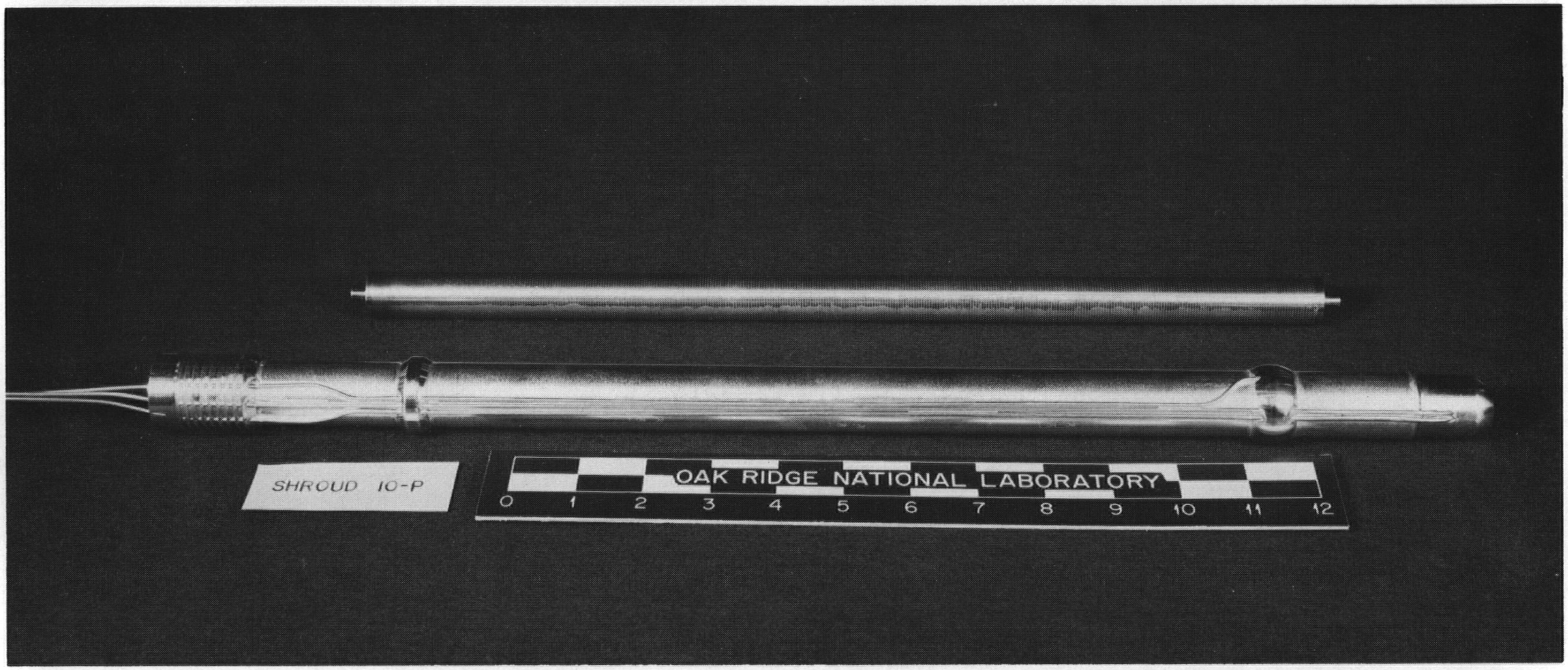

Fig. 32. Loop No. 1 Fuel Element and Shroud. Note that fuel element has wires brazed to the surface for roughening to enhance heat transfer.

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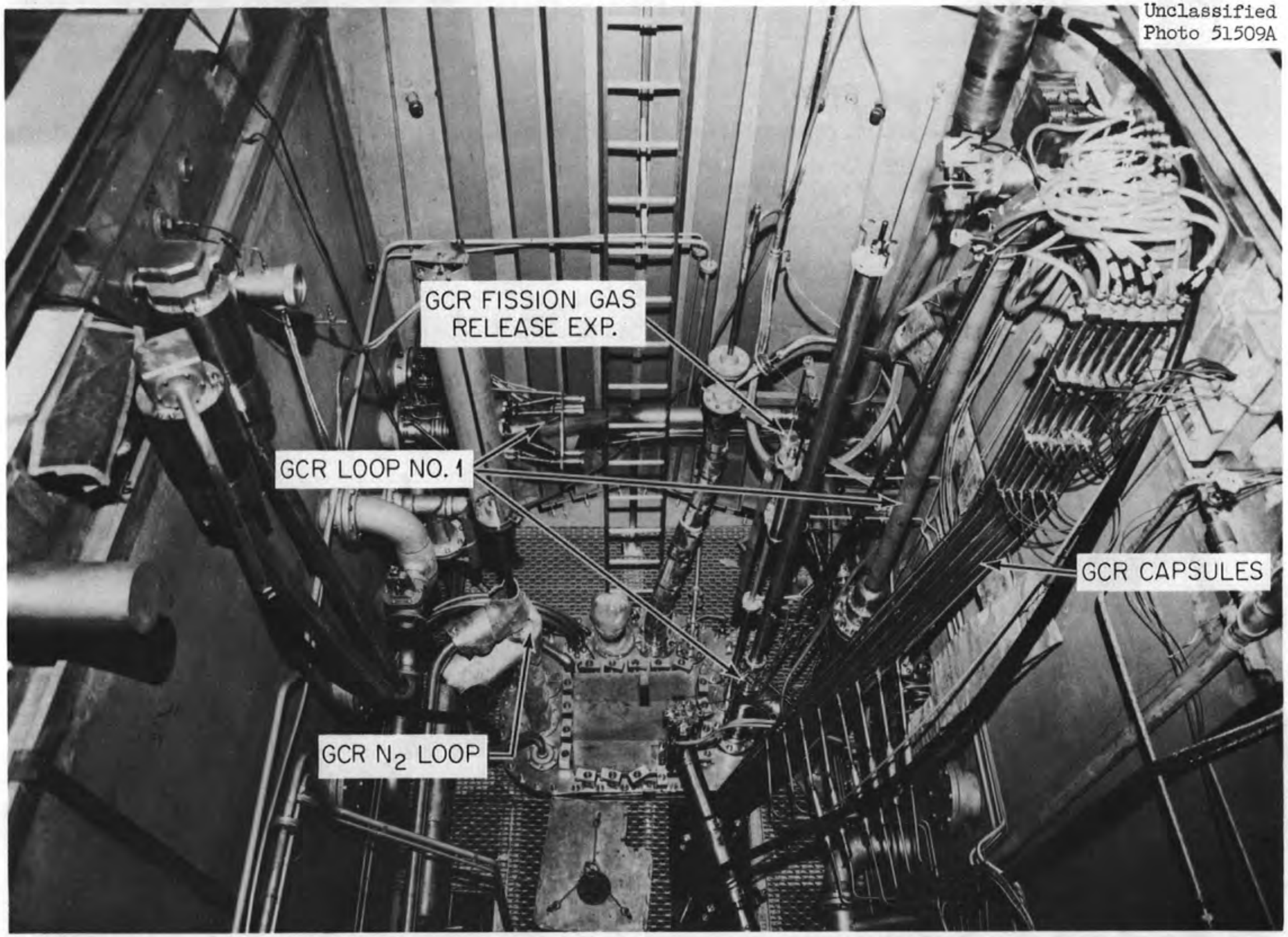

Fig. 33. Oak Ridge Research Reactor with Gas-Cooled Reactor Experiments Underway.

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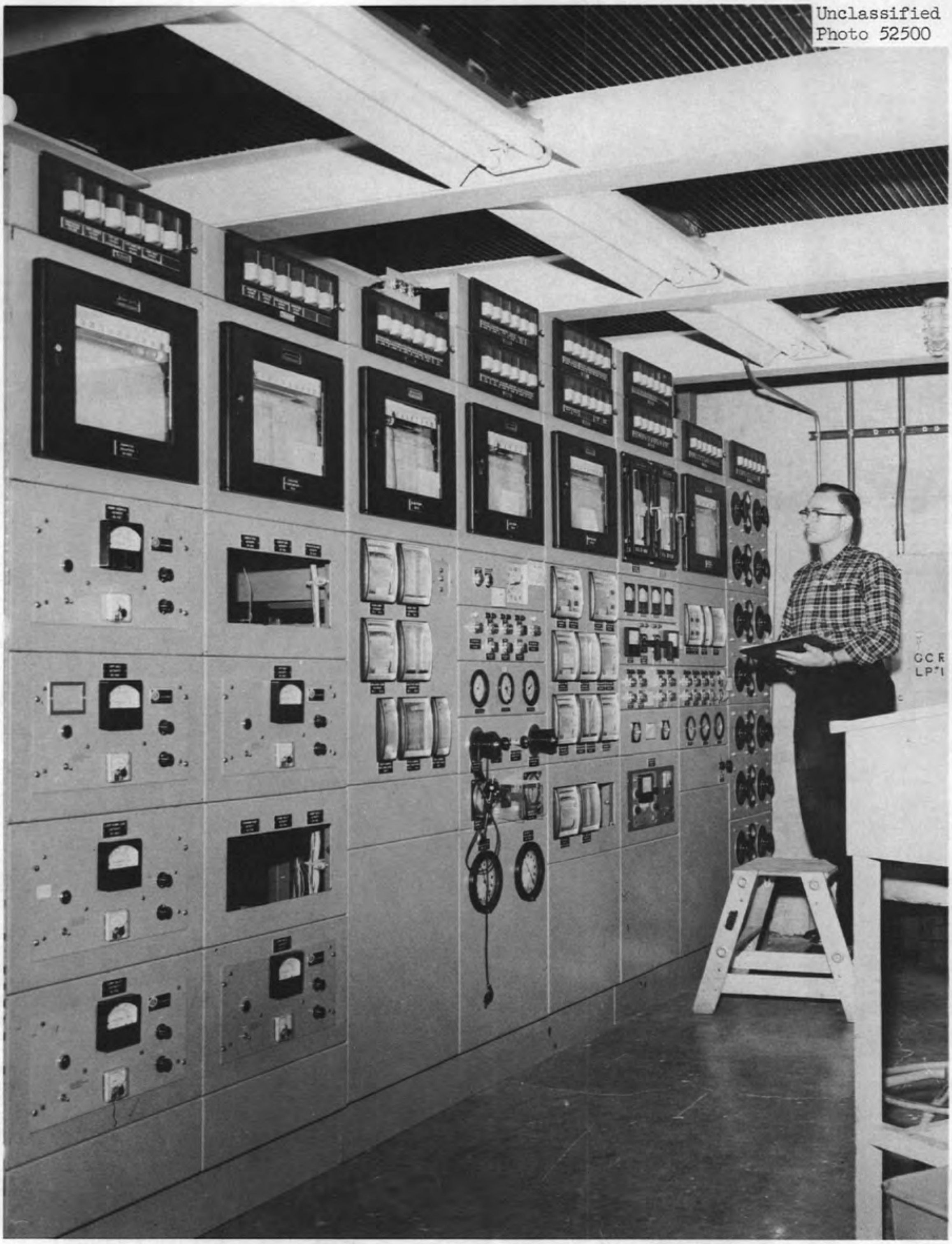

Fig. 34. GCR-ORR Loop No. 1 Instrument Panel.

Table 4. Tests Conducted in Loop No. 1

Test Number	Sample	Power (Btu/hr·ft)	Maximum Cladding Temperature (°F)	Fuel Central Temperature (°F)
1	Pressure vessel steel		550	
2	Pressure vessel steel		550	
5	EGCR type fuel element	26,000	1450	1900
6B	EGCR type fuel element	26,000	1200	1900
7A	EGCR type fuel element	28,000	1450	2100
7B	EGCR type fuel element	28,000	1450	2100
7C	EGCR type fuel element	28,000	1450	2100
9	EGCR type fuel element	40,000	1540	2400
8	Fuel element with transverse fins	40,000	1540	2400
8S	Fuel element with transverse fins	40,000	1540	(a)
10P1	Fuel element with transverse fins	65,000	1540	3500
10P2	Fuel element with transverse fins	50,000	1300	2600
7D	Ventilated fuel element	26,000	1500	2100
11M	Fuel element with transverse fins	75,000	1500	3300

[a]Thermocouple failed.

ORR Gas-Cooled Loop No. 2

This facility provides for the irradiation of unclad fuel elements that may release fission products directly to the gas stream and for studies of fission-product behavior in a complex heat transfer system. A recirculating high-temperature helium loop is utilized for cooling the fuel and to simulate reactor systems.[28] The irradiation test region located in the south beam hole of the ORR will accommodate fuel specimens up to 2 3/4 in. in diameter and 9 in. long. The piping immediately behind the fuel test region is arranged to accommodate various separately cooled or heated surfaces for studies of fission-product deposition. These surfaces are built integrally with the fuel test assembly and are removed with the fuel for postirradiation examination. Sectional views of the loop test region are shown in Figs. 35 and 36. A heavily shielded carrier is provided for transfer of the irradiated specimen from the loop cell to a dismantling hot cell where critical parts are removed for examination in smaller cells.

The loop consists of 2 1/2-in.-diam, sched.-40, 300-series stainless steel pipe, compressors, an 80-kw electric heater, an evaporative cooler, a regenerative heat exchanger, a filter, the test section, and appropriate gas cleanup equipment. Instrumentation is provided to measure flows, pressures, temperatures, and radiation levels. Conversion of all gas-pressure signals to electric output is provided consistent with the design of the loop containment. Loop controls are automatic to the extent possible and provision is made for reactor shutdown prior to development of abnormal conditions which would jeopardize the experiment, the loop, or its containment. An overall flow diagram of the loop is shown in Fig. 37.

A shielded full-flow filter is provided for general cleanup of the loop gas and, particularly, to collect fragments of unclad fuel elements which might be circulated in the loop. A side-stream purification system removes chemical and radioactive contaminants from the helium during normal operation and, by proper valve settings, can be used to clean loop gas for discharge to the disposal stack. The design of the purification system is based on a limited flow of gas through a copper oxide bed, molecular sieve, and carbon trap. The carbon trap reduces activity by absorbing iodine and by delaying the noble fission gases for several half-lives of radioactive decay. Krypton holdup is approximately 40 hr.

A sampling system is provided to remove helium coolant for quantitative analysis of noble fission gases and corrosion impurities, such as CO, CO_2, H_2, H_2O, and CH_4. Radioactive components are analyzed with a scintillation detector and a multichannel analyzer, which are also used for fission-gas-release measurements in the ORR poolside capsules. A gas chromatograph is provided for on-line determination of chemical impurities. Impurity levels are easily maintained below 10 ppm during loop operation. The concentration of CO and CO_2 can be held below 1 ppm or increased (by additions) to very high values, if desired, for studies of carbon transport effects.

All primary system components, including compressors and heat transfer and gas cleanup equipment, are located in a shielded cell adjacent to the ORR reactor pool wall. The arrangements of equipment and the cell design are shown in Figs. 38 and 39. The instrument panel is shown in Fig. 40. A hot-cell window and an omniscope provide for observation of the loop equipment during operation. Certain remote operations can be handled by a manipulator and a cell crane, which are controlled at the cell window. Individual components, in addition to being located in the cell, are shielded to permit operation with heavily contaminated gas streams without buildup of activity to levels that would prevent access by operators and maintenance personnel during reactor shutdown periods.

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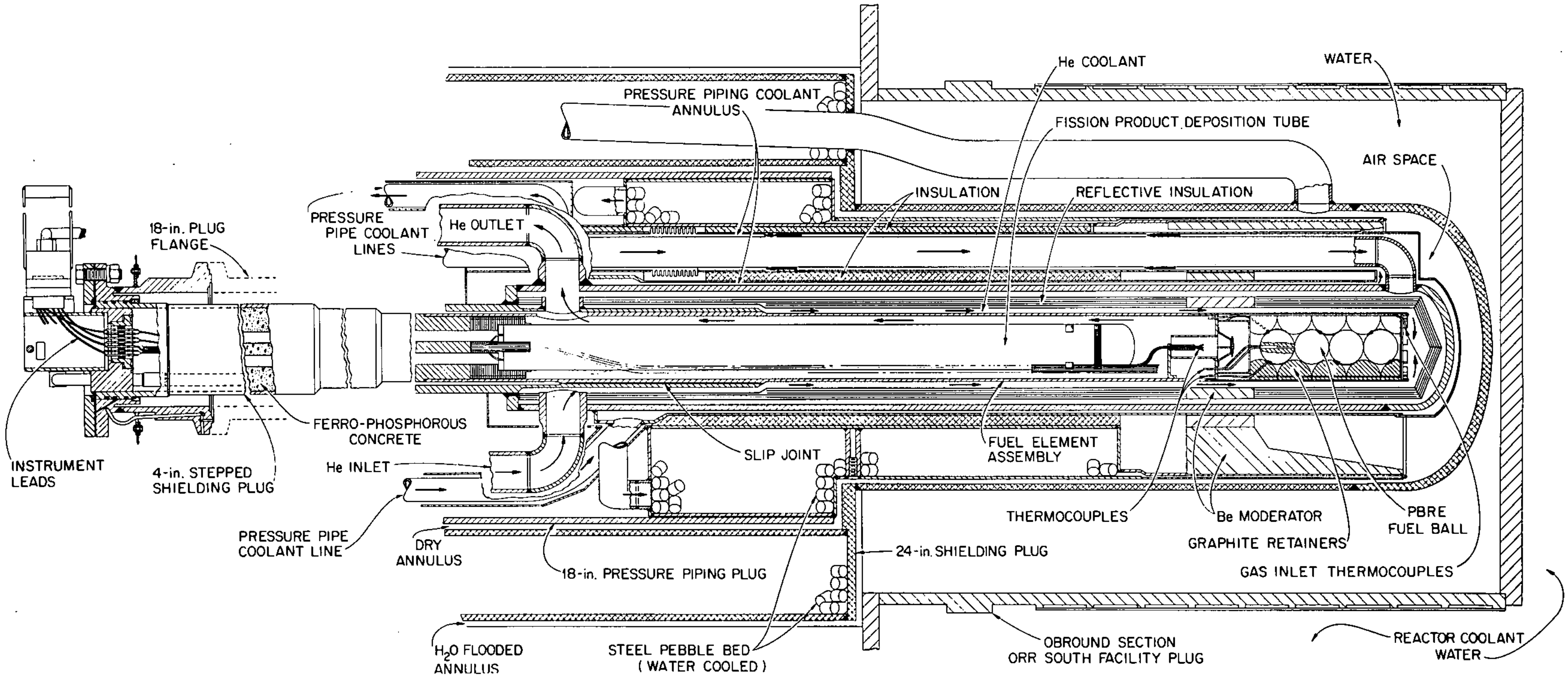

Fig. 35. Assembly for Tests of Fueled-Graphite Spheres in GCR-ORR Loop No. 2.

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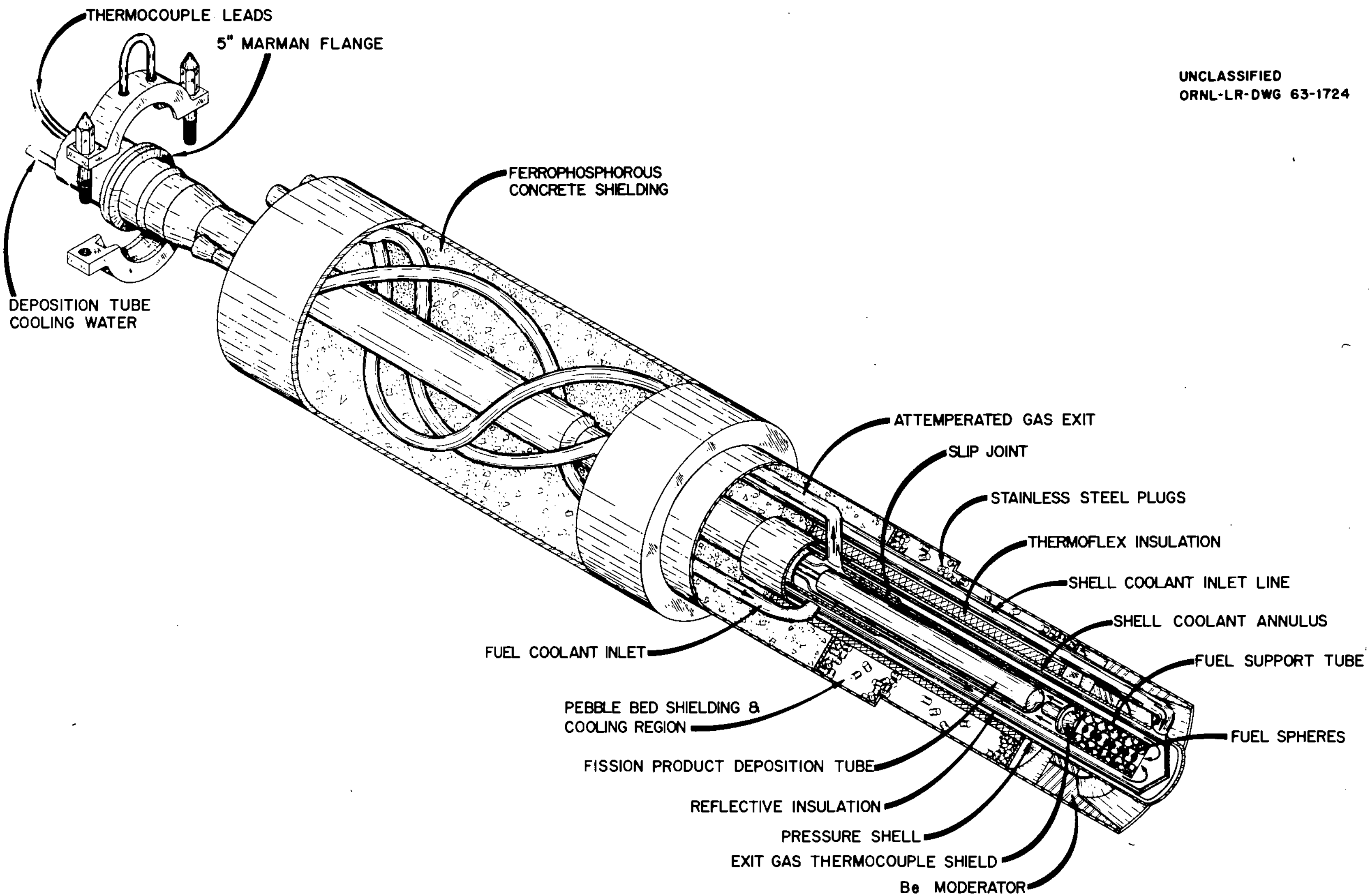

Fig. 36. GCR-ORR Loop No. 2 In-Pile Section.

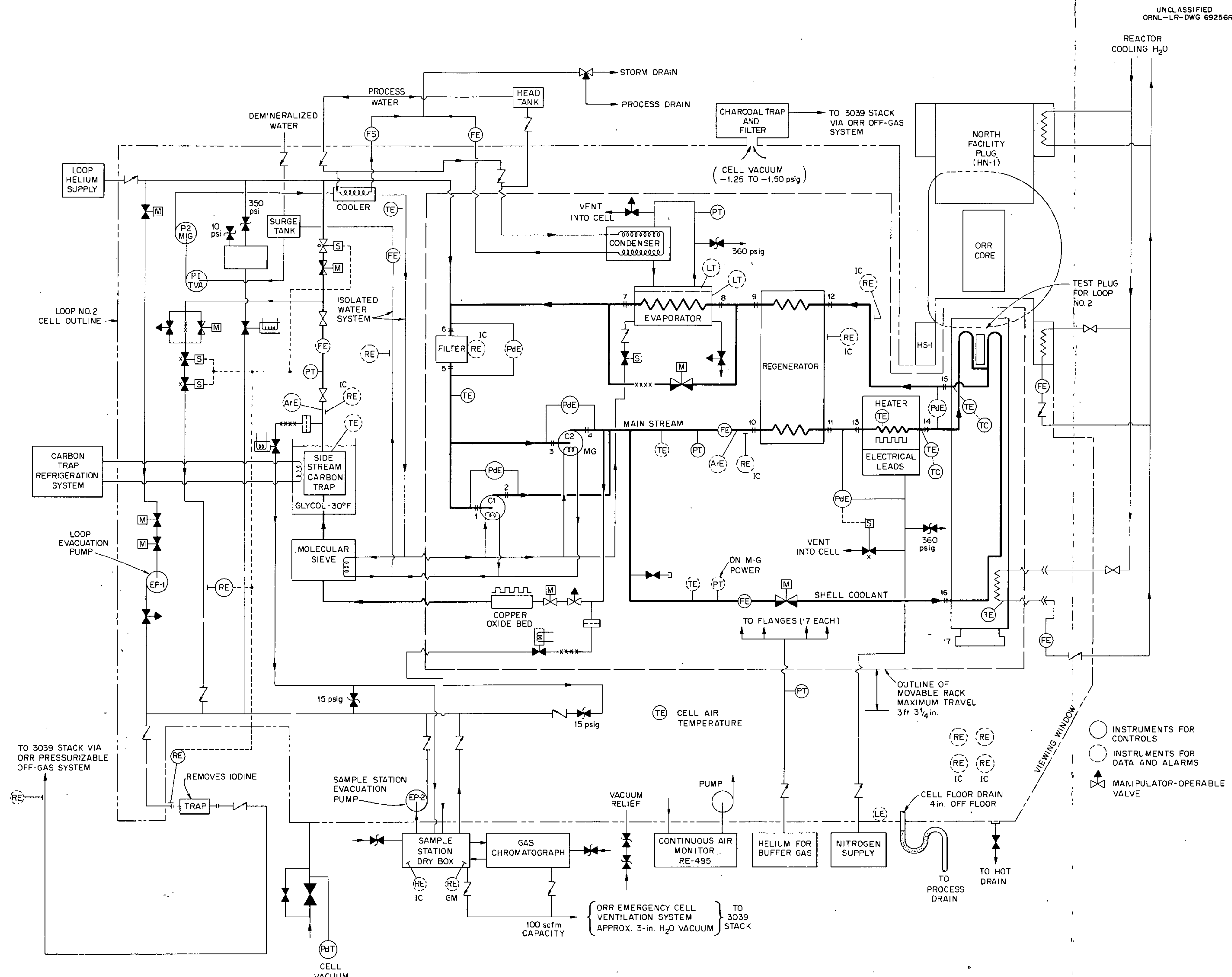

Fig. 37. Composite Flow Diagram of GCR-ORR Loop No. 2.

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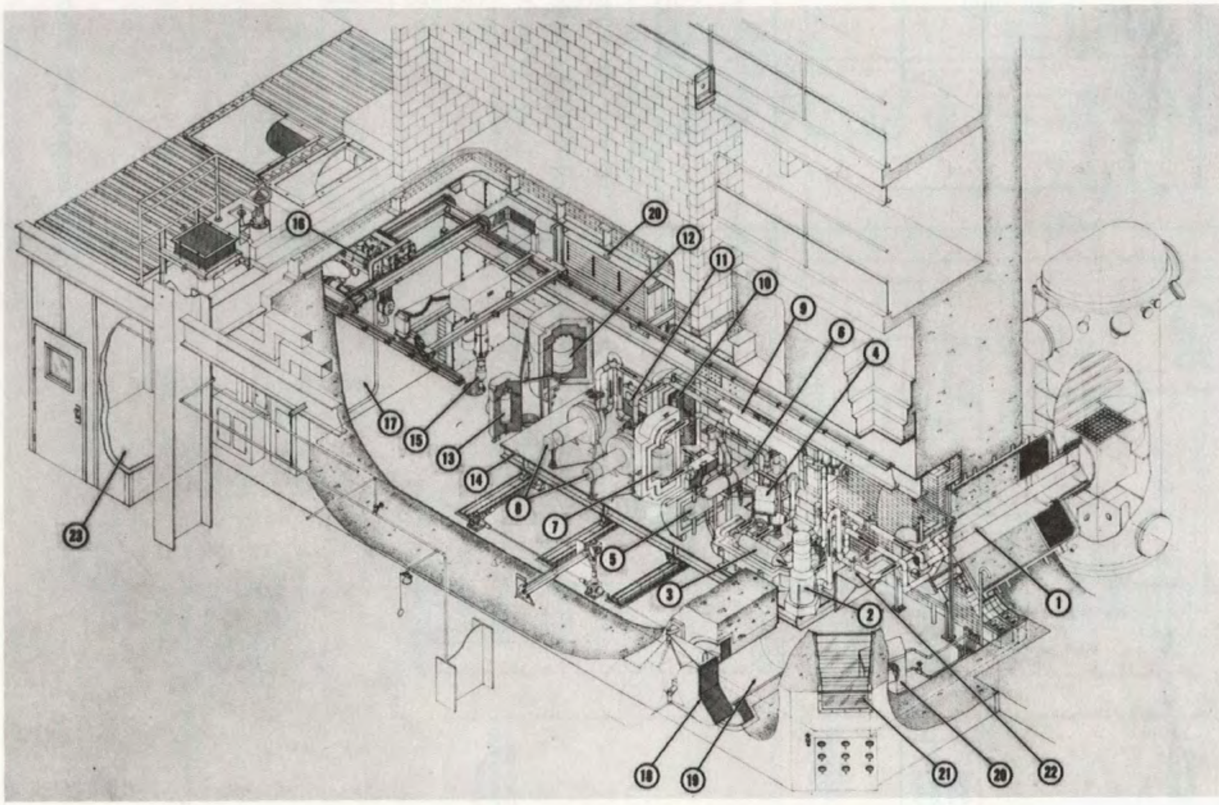

1. FUEL TEST TUBE
2. HEATER
3. REGENERATER
4. EVAPORATOR BY-PASS VALVE
5. EVAPORATOR
6. CONDENSER
7. FILTER
8. COMPRESSORS
9. SHELL COOLANT STREAM
10. CuO BED
11. SIDE STREAM COOLER
12. SIDE STREAM CARBON TRAP
13. MOLECULAR SIEVE
14. MOVABLE RACK
15. REMOTE MANIPULATOR
16. 5-TON CRANE
17. PERSONNEL ACCESS DOOR
18. EXTERNAL SHIELD DOOR
19. TEST PLUG REMOVAL SLEEVE
20. SPACE COOLERS
21. VIEWING WINDOW
22. MARMON SEAL FLANGE
23. AIR LOCK

Fig. 38. Diagram of GCR-ORR Loop No. 2.

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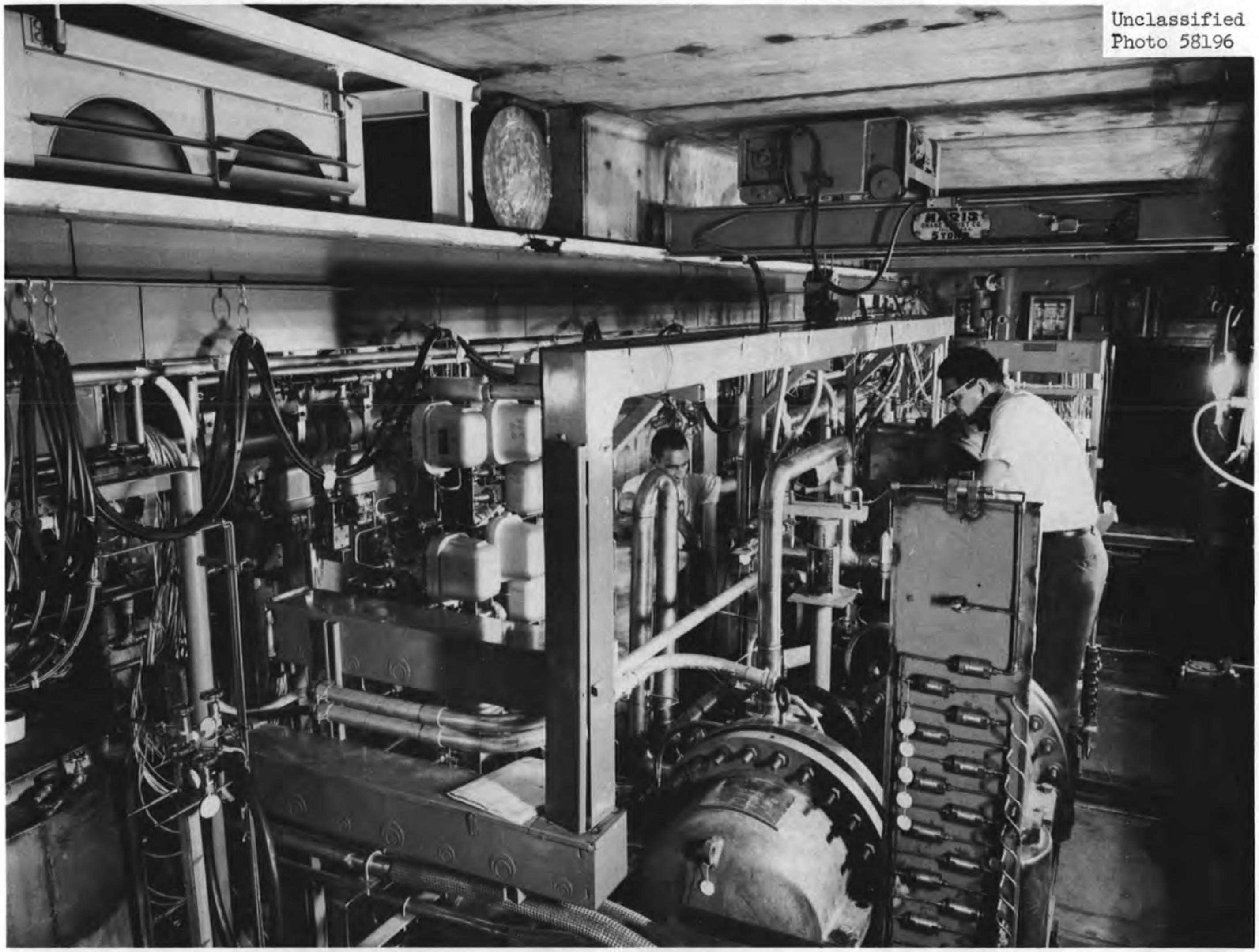

Fig. 39. View of Loop No. 2 Equipment in the Containment Cell. A compressor housing is prominent in the lower right foreground.

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Fig. 40. Instrument Control Panel for Loop No. 2.

Three experiments have been conducted in the loop, as listed in Table 5. The first utilized a small quantity of UO_2 as a calibration test sample for radioactivity release and for determining the operability of the loop equipment for handling and detecting fission products. The second and third tests involved spherical elements containing pyrolytic-carbon-coated UC_2 fuel in a graphite matrix structure.[17,18] Each test has proceeded smoothly during operation. Removal of the irradiated pieces following the first two tests has been accomplished routinely, and the third test is in progress.

Table 5. Fuel Tests Conducted in Loop No. 2

Type of Test	Fuel Element	Power (kw)	Fuel Central Temperature (°F)
Shakedown	UO_2 film	Negligible	1100
Fuel stability	Four spheres, 1 1/2 in. in diameter, consisting of pyrolytic-carbon-coated particles in a graphite matrix	4	1400
Fuel stability	Three spheres, 2.38 in. in diameter, consisting of pyrolytic-carbon-coated particles in a graphite matrix	5	1650

ORR Pressurized-Water Loop

This test facility, in which fuel and other materials can be subjected to radiation and other environmental conditions simulating a pressurized-water reactor system, has been operated in the Oak Ridge Research Reactor since December 1959. It was designed for tests of stainless steel-clad fuel elements containing UO_2 or other ceramic fuels. The initial tests in the loop were conducted to evaluate fuel elements for N.S. SAVANNAH replacement cores.[29,30] Pellets, swaged-powder, and vibration-compacted bulk fuels in cylindrical elements and dispersion fuels in flat coupons and hollow cylinders have been irradiated. The A-1 and A-2 core positions of the ORR are utilized to accommodate multiple element assemblies. The test loop is designed to recirculate water at 2500 psig, 650°F, and 80 gpm with a heat removal capacity of 300 kw.[31] The piping within the reactor is arranged as a U tube with straight vertical access through the reactor vessel cover. An isometric view of the loop as installed at the ORR is shown in Fig. 41, and a schematic flow diagram

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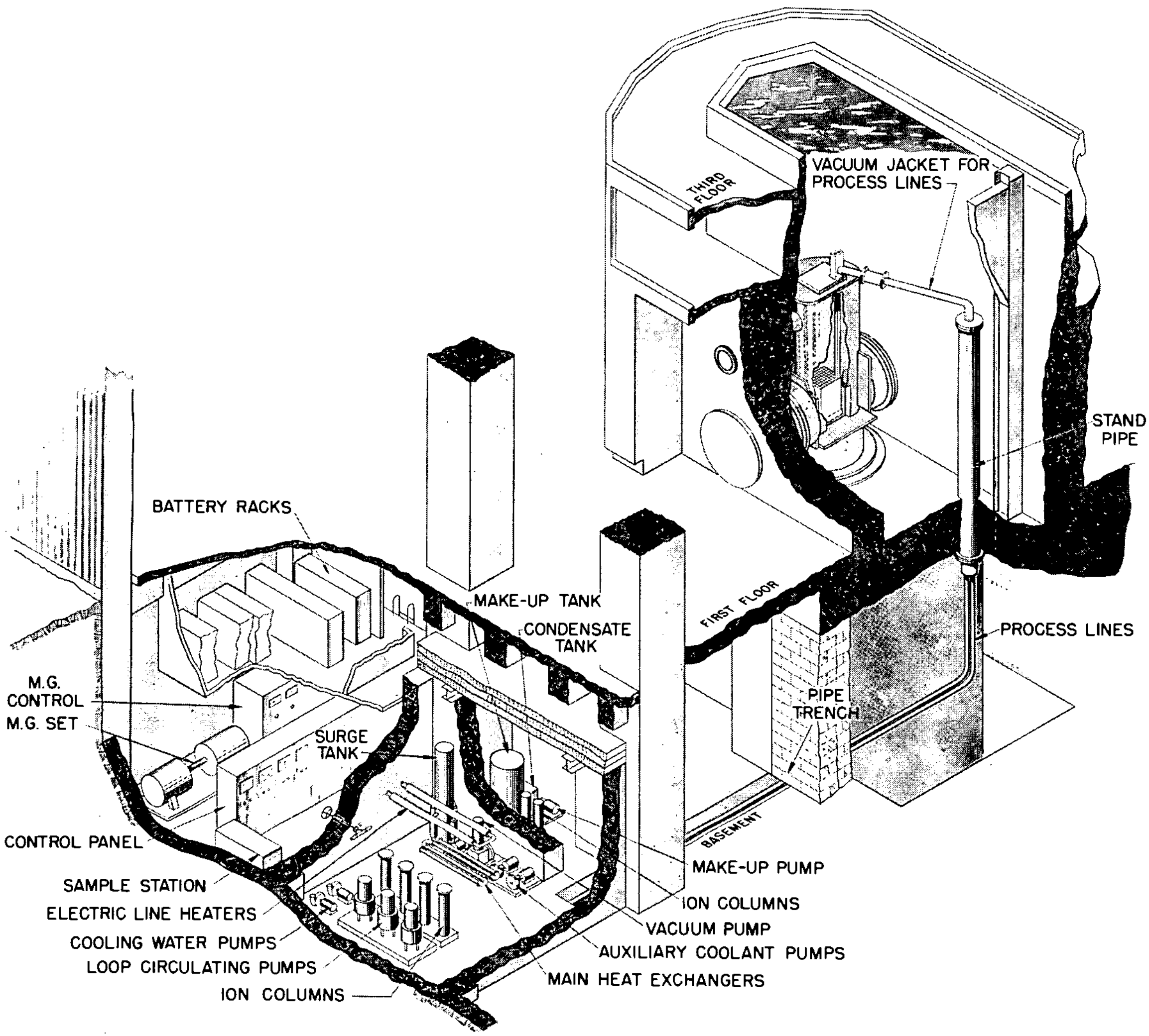

Fig. 41. Pressurized-Water Loop in the ORR.

is presented in Fig. 42. The in-pile piping is type 316 stainless steel; elsewhere, type 347 stainless steel was used. The maximum perturbed thermal-neutron flux is 7×10^{13} neutrons/cm^2·sec, and the peak gamma heat is approximately 5 w/g.

The legs of the U tube are encased in stainless steel vacuum jackets, which provide thermal insulation and secondary containment. The assembly fits into two modified ORR experiment core-pieces, as shown in Fig. 43. Each is sealed with an O-ring gasket in a "breachlock" flange closure above the reactor vessel, which is opened for insertion and removal of test assemblies. Above this point, 11 ft of pool water serves as a shield during the removal operation. The arrangement of the ORR pool and hot cell is convenient and safe for test-specimen removal, storage, inspection, and preparation for shipment. A special containment vessel and equipment for removal of ruptured fuel specimens is available; however, no serious fuel failures have occurred. Photographs of typical test fuel element assemblies are shown in Figs. 44 and 45.

In order to ensure reliability of cooling for fuel elements, the three main loop pumps are arranged in parallel with check valves and an electrical control system that will start another pump automatically if the operating unit fails. A dc-ac motor-generator set with rectifier and batteries operates continuously and is available to provide the power needs for loop cooling. It also serves as a second power source for GCR-ORR loops 1 and 2. An isolated water system separates the loop primary system from the reactor pool cooling water system to which the heat generated in the loop is dissipated. The loop is pressurized from a separately heated tank equipped with vapor flash nozzles and vents for degassing. The loop is well equipped with fill, vent, and drain lines that terminate at the sampling station. In Fig. 46, the sampling station is in the background with the loop control panel on the right and the cell shielding wall with loop valve extension handles at the left.

An out-of-pile test section is located with the auxiliary equipment in a shielded cell in the basement of the ORR building. This provides convenient access for insertion of nonnuclear experimental equipment, such as electrically heated surfaces and special filters. Water samples can be removed at loop operating temperatures. Ion exchangers are provided in the loop fill system and in a bypass stream to maintain the necessary water purity and pH. Hydrogen additions can be made to scavenge oxygen and reduce radiolytic decomposition. A small high-temperature bypass stream makes possible tests of small filtration devices located at the sample station.

All loop components have operated satisfactorily. Leakage has been negligible, with makeup required only for replacement of the water removed by sampling. Oxygen concentrations are consistently below 0.020 ppm with addition of hydrogen. Particulate matter is also found to be at low levels of concentration: ~1 to 4 ppm. This has resulted in low contamination in the equipment room; the activity is usually below personnel tolerance levels. Direct radiation levels in the equipment room are near

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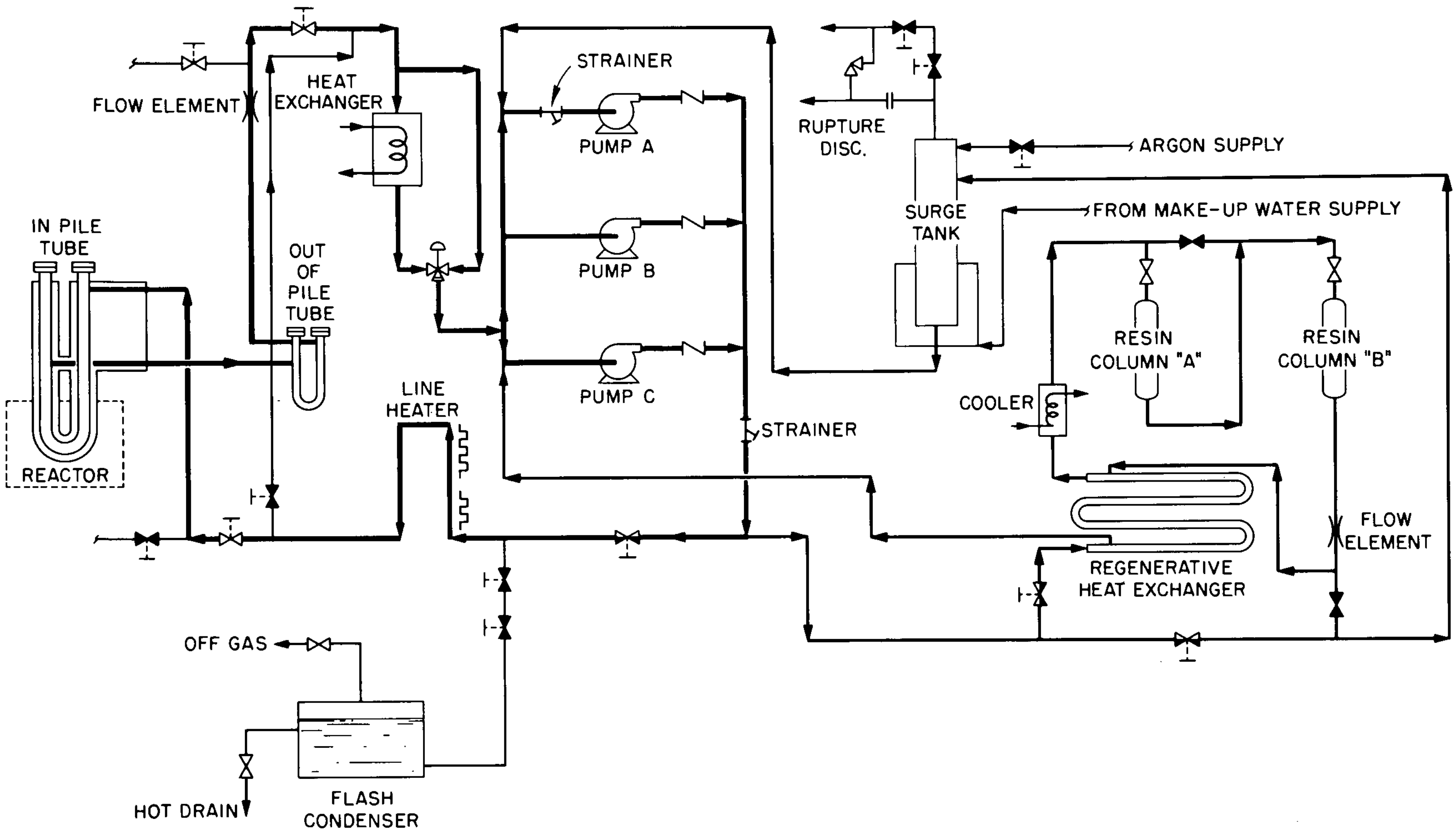

Fig. 42. Simplified Flow Diagram of Pressurized-Water Loop.

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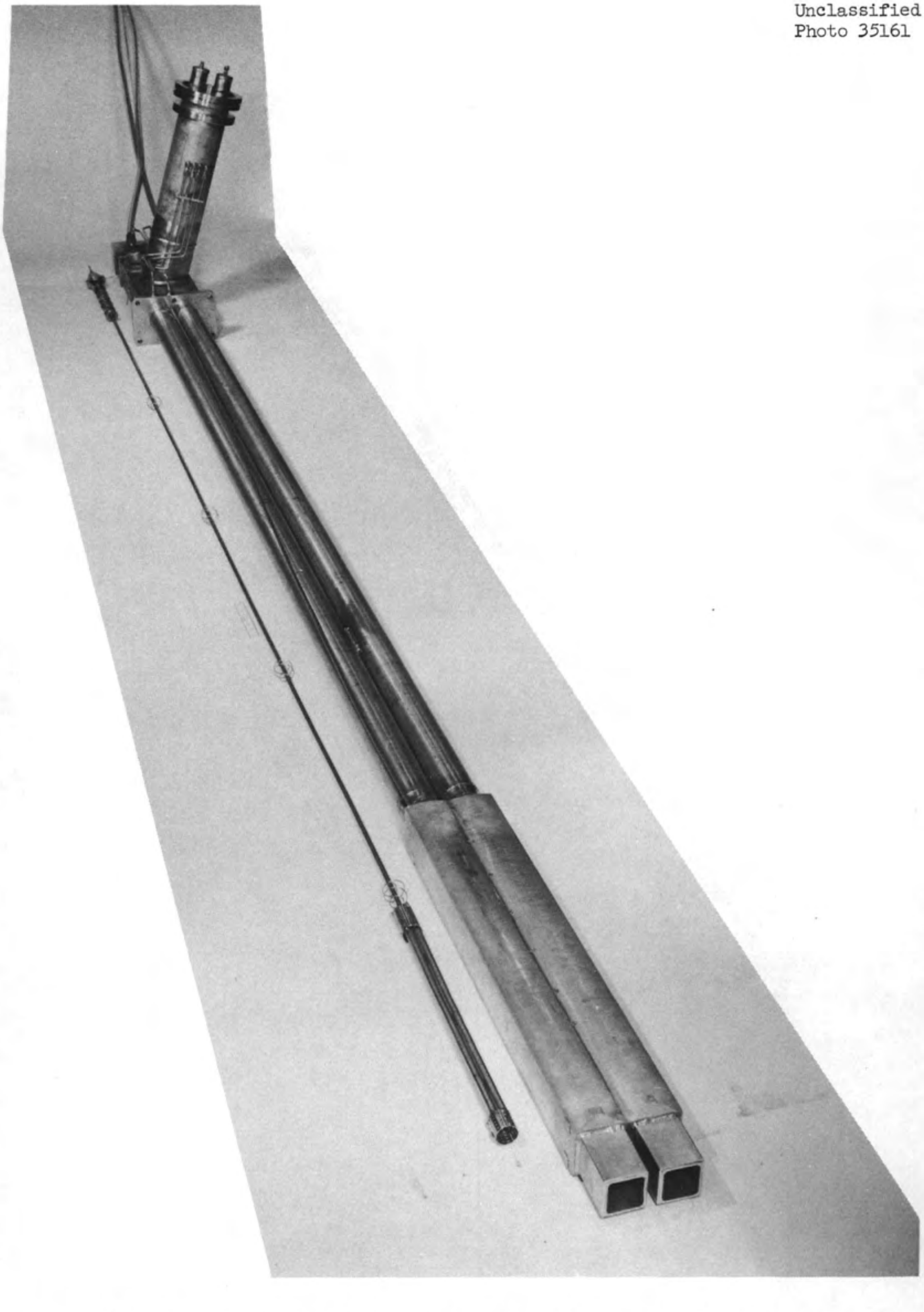

Fig. 43. In-Pile U-Tube Assembly for Pressurized-Water Loop. Tee section at the top is welded to loop. Modified ORR core pieces for positions A-1 and A-2 are in the foreground. The experiment assembly and support tube for one leg are shown at the left.

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Fig. 44. Two Three-Pin Assemblies for Irradiation in the Pressurized-Water Loop.

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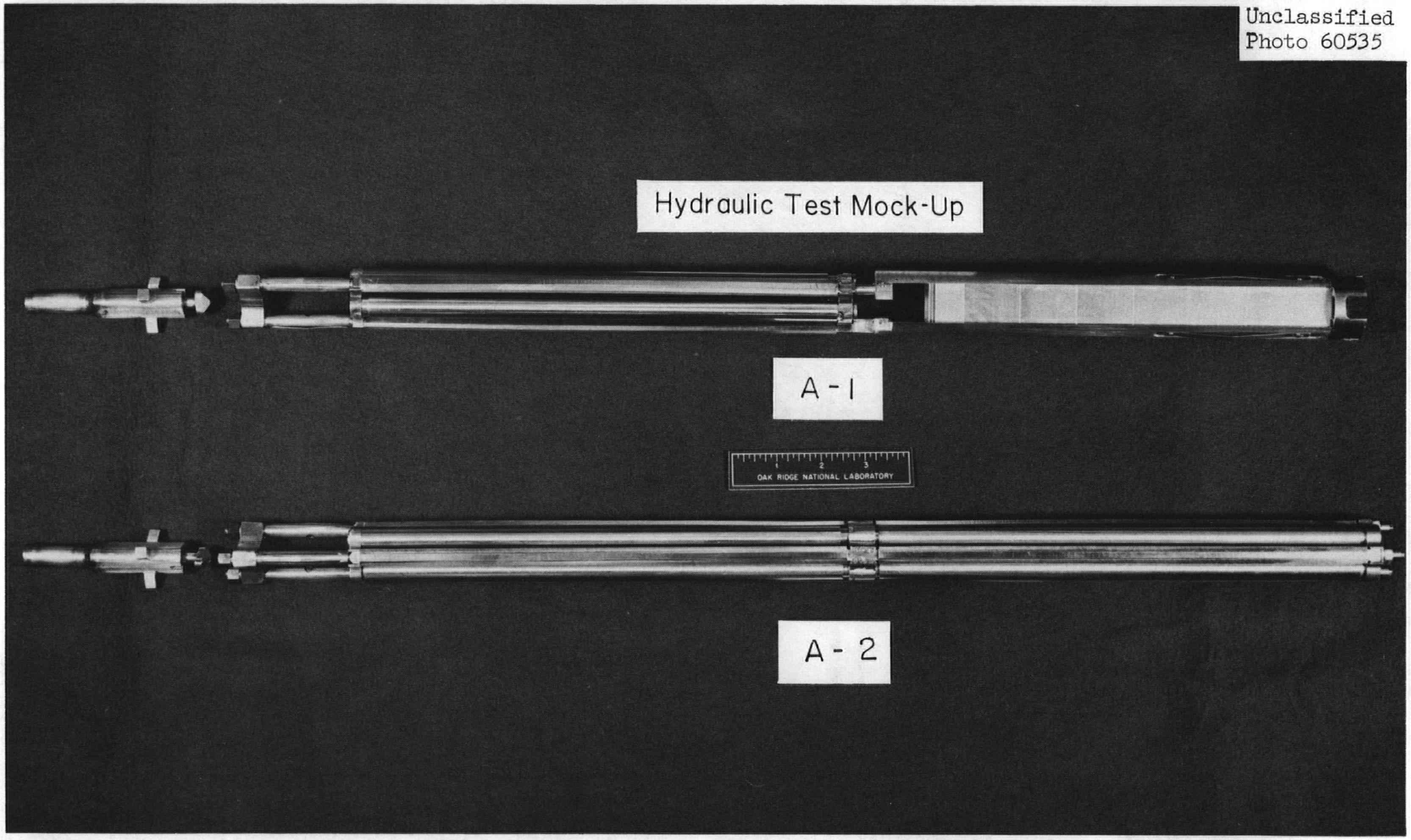

Fig. 45. Army-Martin Stainless Steel Dummy Fuel Specimens.

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Fig. 46. Operating Area for ORR Pressurized-Water Loop. Control valve handles at left, instrument panel at right, and water sampling station in background.

working tolerance levels at shutdown and have not exceeded 75 mr/hr during operation. The sample station area also is kept free from contamination by good sampling techniques.

Low leakage rates and excellent performance of the loop make possible carefully controlled water-chemistry experiments of long duration. Several experiments with water purification have been conducted, particularly with Magnetite filters for removing crud, and improved analytical techniques for water-chemistry measurements have been developed. The water chemistry program objective is development of improved equipment for the removal of impurities at concentrations less than 1 ppm.

A fixture has been provided in which a fuel specimen assembly irradiated in the loop can be removed from its support conduit for examination. The element can be rotated in two planes while in the fixture to provide for viewing and photographing of exposed surfaces through a periscope. Following examination, the assembly can be reattached to the support and reinserted in the loop for further irradiation. Should the element condition have deteriorated so that further irradiation is not desirable, it can be transferred from the fixture to the ORR hot cell. A photograph of the device is shown in Fig. 47.

Fuel tests presently under way are in support of the standard package, PM, Army reactor development with fuel specimens provided by the Martin Company Nuclear Division.[32] A summary of fuel elements and test conditions for experiments conducted in the loop is given in Table 6.

MTR Capsules and Loop Equipment

The MTR fuel irradiation test facility was originally developed to operate molten-salt loops for the Aircraft Nuclear Propulsion Program and later for the Molten-Salt Reactor Program,[33] and it has since been modified to accommodate irradiation capsules of various types.[34,35] The 6-in. beam hole at the MTR provides considerable volume at a rather high thermal-neutron flux, $\sim 1 \times 10^{14}$ neutrons/cm^2·sec. The high flux and the conveniences offered by the equipment installed facilitate testing a wide variety of fuel types and configurations.

MTR Loops

The loops as initially installed were compact forced-circulation units for obtaining corrosion data applicable to molten-salt reactors. They were designed to operate in the MTR (HB-3) beam hole. Several tests were conducted with two fused-salt mixtures ($NaF-ZrF_4-UF_4$ and $Li^7-BeF_2-UF_4$) in loops constructed, respectively, of Inconel and INOR-8 (nominal composition: 70% Ni, 16% Mo, 7% Co, 5% Fe, 2% other alloying elements). The conditions for these tests are presented in Table 7. Each loop contained a pump to circulate the molten salt through a hairpin-shaped length

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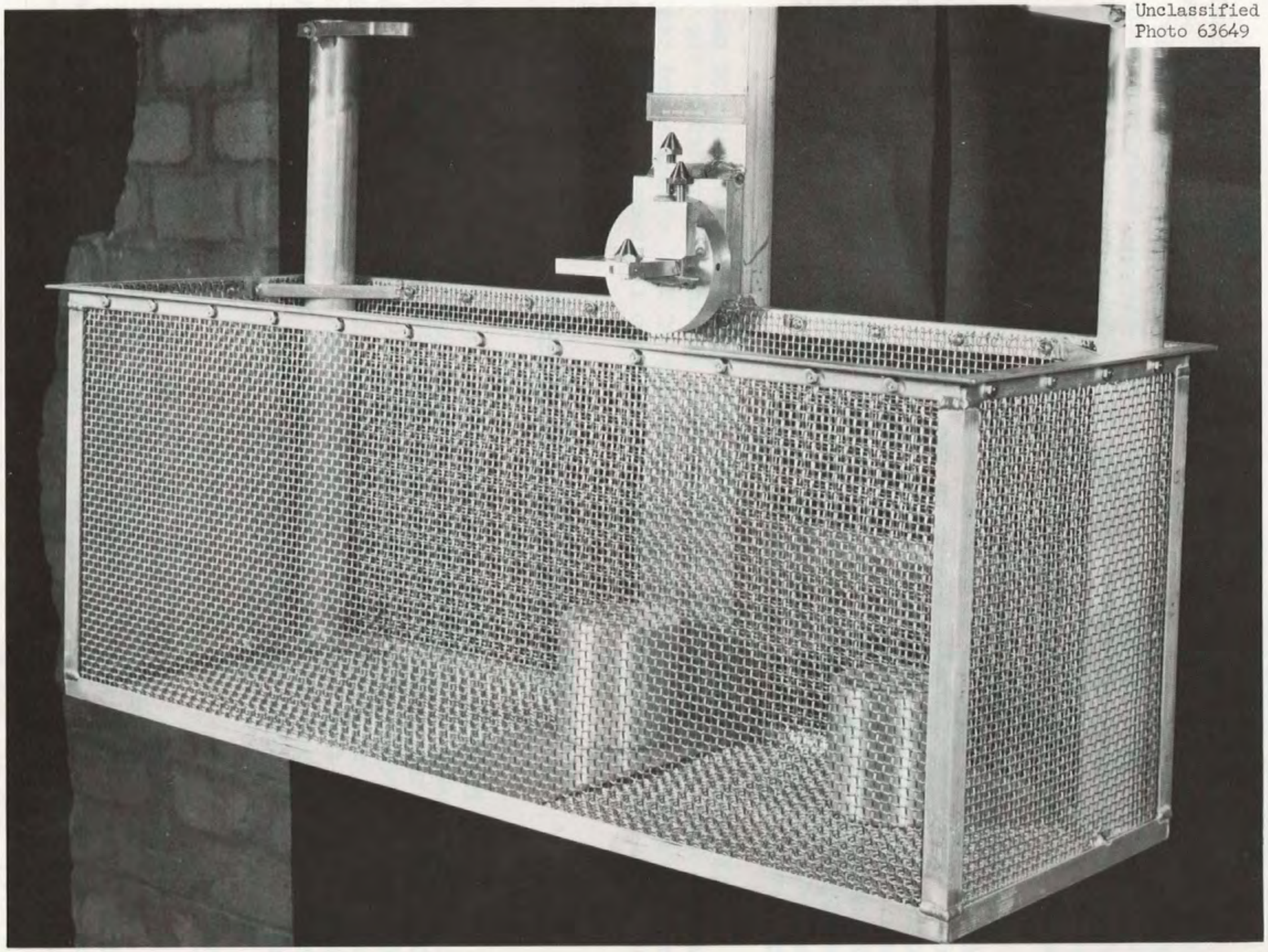

Fig. 47. Fixture for Underwater Examination of Fuel Elements from the Pressurized-Water Loop.

Table 6. Experiments Conducted in the ORR Pressurized-Water Loop

Test No.	Fuel Element Description	Number of Elements	Maximum Power (Btu/hr·ft^2)	Loop Total Power[a] (kw)	Water Temperature (°F)	Water Pressure (psia)
			$\times 10^3$			
1A1	Swaged UO_2, stainless steel clad	3	95	40	517	1750
1A2	Swaged UO_2, stainless steel clad	3	115	40	517	1750
3	Swaged UO_2, stainless steel clad	6	120	40	500	1750
4	Swaged and vibration-compacted UO_2, stainless steel clad	3	275	110	500	1750
5	Swaged and vibration-compacted UO_2, stainless steel clad	3	275	110	500	1750
6	Vibration-compacted UO_2, stainless steel clad	3	400	130	500	1750
7	Vibration-compacted UO_2, stainless steel clad	3	550	110	480	1750
8	Vibration-compacted UO_2, stainless steel clad	3	425	110	480	1750
9	UO_2 pellets in thin stainless steel cladding (collapsing)	3	270	110	480	1750
L-1	Vibration-compacted ThO_2-UO_2, stainless steel clad	3	400	110	480	1750
PM-A1-1	Stainless steel-UO_2 dispersion tubes and coupons	27	800	50	355	1300
PM-A2-1	Stainless steel-UO_2 dispersion tubes	6	1200	200	355	1300

[a] Maximum total heat removed by loop during irradiation of fuel element.

Table 7. In-Pile Loop Tests of Circulating-Molten-Salt Fuel

Loop No.	Container Material	Fused Salt Fuel Designation	Maximum Temperature (°F)	Average Power Density[a] (w/cm^3)	Total Fission Power (kw)
3	Inconel	44[b]	1500	200	27
4	Inconel	44	1500	232	31
6	Inconel	44	1600	250	34
7	INOR-8	130[c]	1300	66	9
8	INOR-8	130	1300	66	9

[a]Total loop heat generation divided by total circulating fuel inventory.

[b]Fused salt 44 was $NaF-ZrF_4-UF_4$ (53.5-40-6.5 mole %; m.p., 1000°F).

[c]Fused salt 130 was $Li^7F-BeF_2-UF_4$ (62-37-1 mole %; m.p., 860°F).

of 1/8-in. sched.-40 pipe, as shown in the isometric drawing of Fig. 48. The pipe was coiled at the forward high-flux end to increase the integrated neutron exposure. A schematic flow diagram for one of the loops is given in Fig. 49. The regenerative turbine-type pump shown in Fig. 50 was developed specifically for this loop. The sump behind the impeller accommodated leakage along the shaft, provided a fluid expansion volume, and afforded the free surface from which fission gases were released to the purge system. A special heat exchanger and other items of equipment were also designed for use in these loops. An overall view of the test facility as used for loops is shown in Fig. 51.

Although the equipment for loop operation is no longer intact, many of the components have been retained. The facility presently affords electrical heating for capsules, gas purging, water cooling, monitoring of effluent lines for radioactivity, large charcoal traps for accumulation of fission gases, sampling stations, and extensive instrumentation. Convenient mechanisms have been provided for installation of test assemblies in the beam hole and for mechanical adjustment of the specimen position in the beam hole during reactor operation to obtain the desired flux for the experimental fuel within the gradient available.

Photographs showing loops in various stages of construction are presented in Figs. 52 through 56. Equipment for removing large volumes of helium purge gas for analysis of chemical impurities and fission-product gases is shown in Fig. 57. The instrument panel used for both loop and capsule tests is shown in Fig. 58.

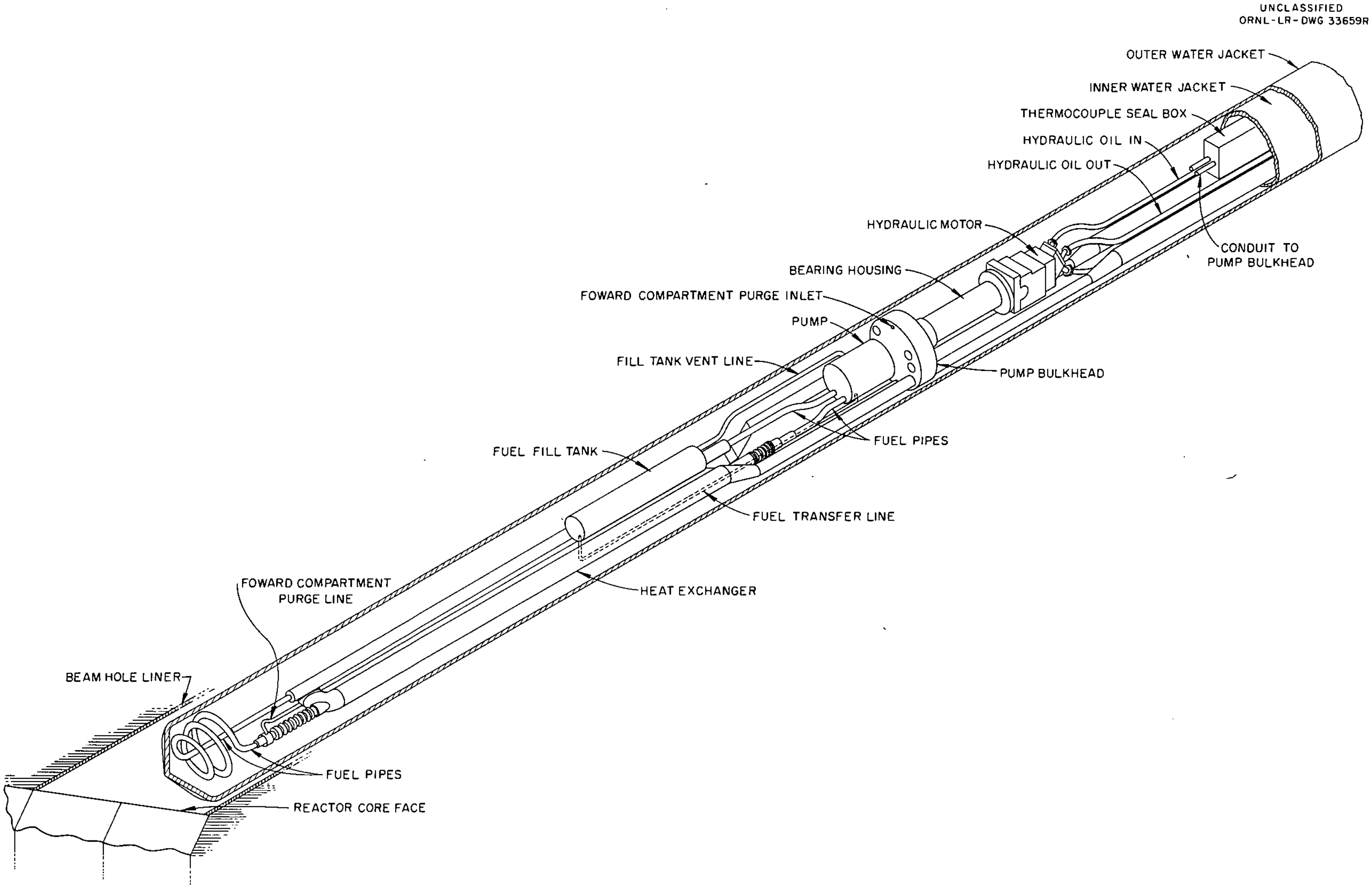

Fig. 48. Diagram of Circulating-Fused-Salt Fuel Irradiation Test Loop.

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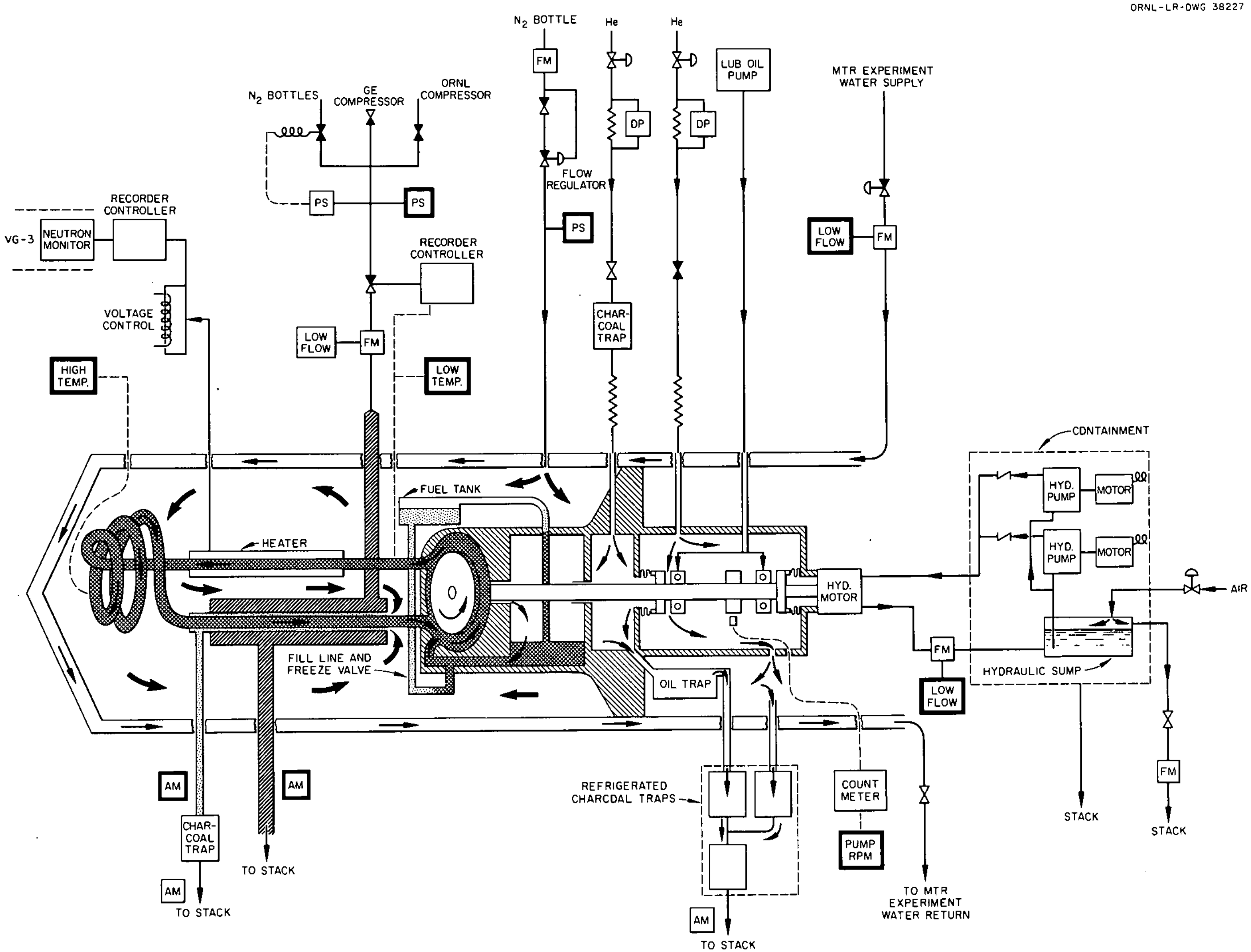

Fig. 49. Flow Diagram for ORNL-MTR-44 Circulating-Fused-Salt Fuel Irradiation Test Loop.

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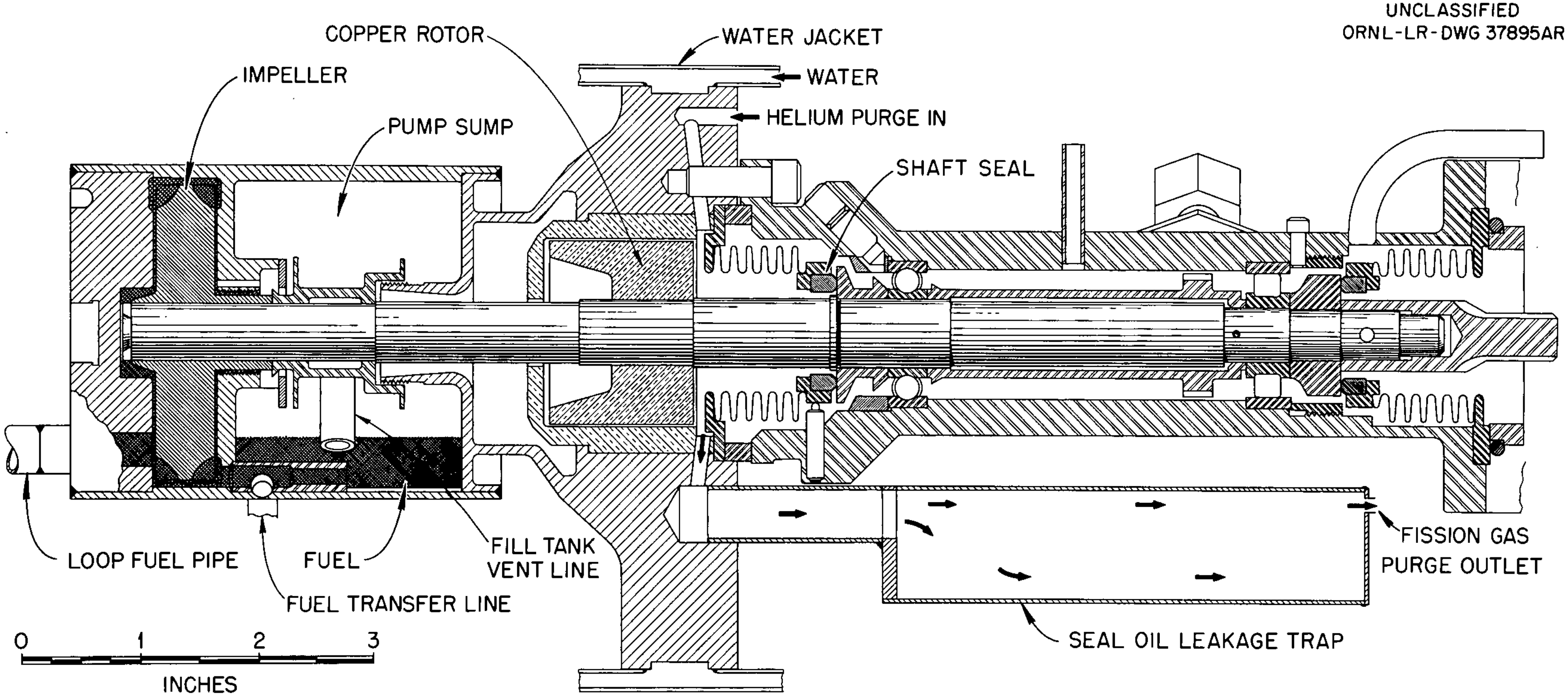

Fig. 50. Fuel Pump for Fused-Salt In-Pile Loop.

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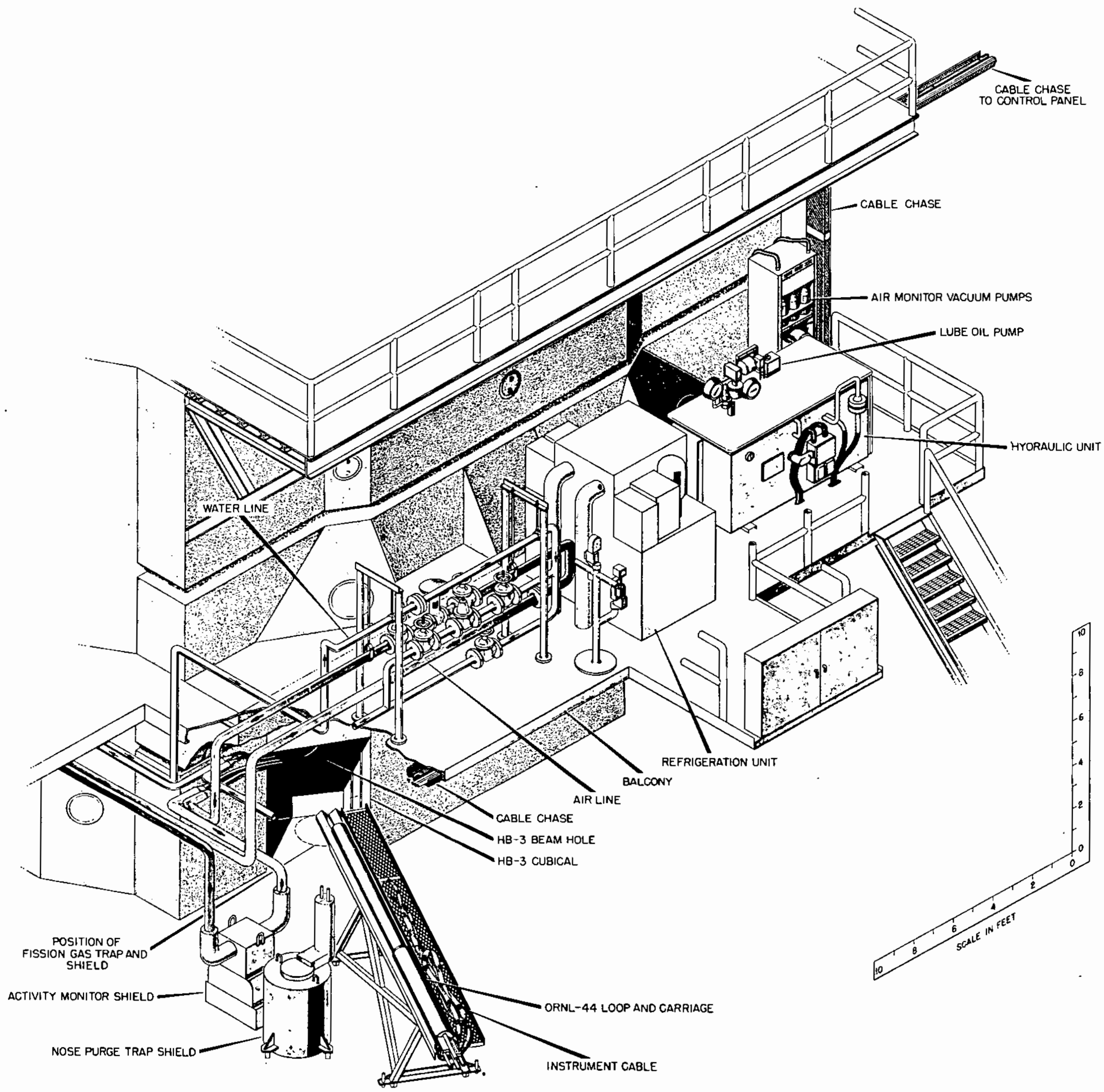

Fig. 51. Irradiation Facility at the MTR HB-3 Beam Hole.

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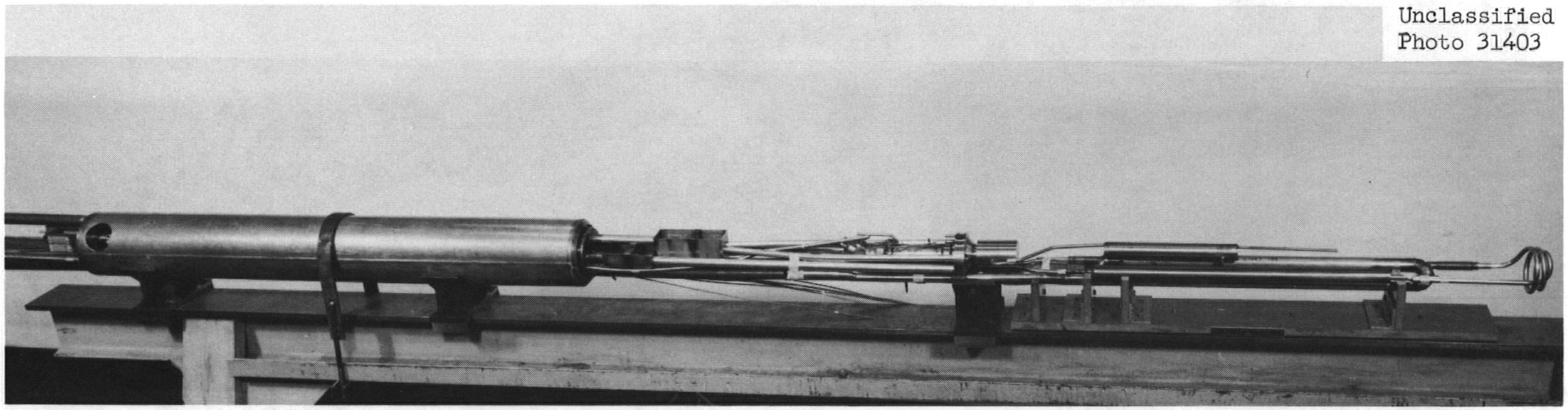

Fig. 52. Overall View of Molten-Salt Loop with Shielding Plug Attached.

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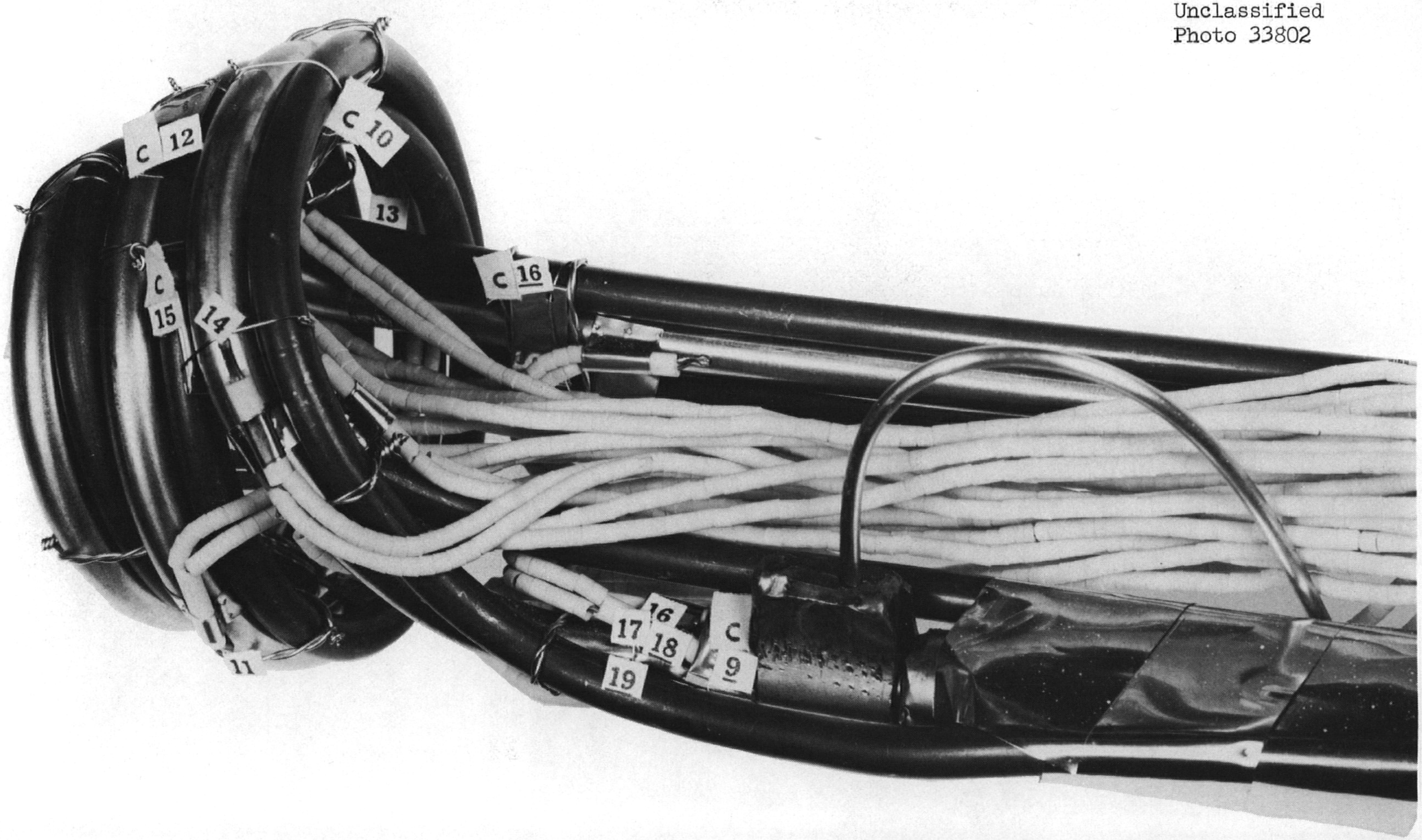

Fig. 53. Closeup of Molten-Salt Loop Nose Coil with Heaters Installed and Thermocouples Attached.

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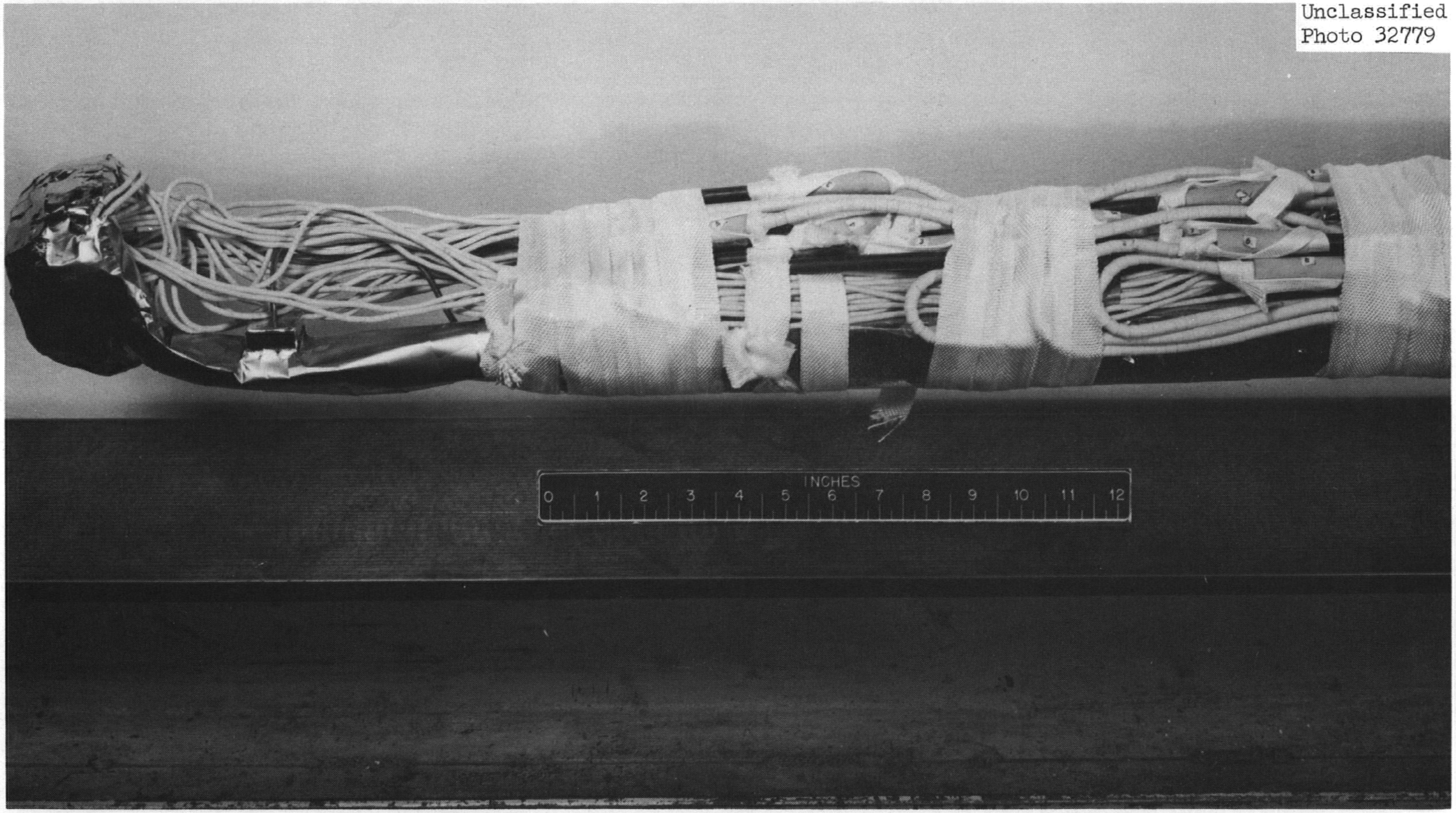

Fig. 54. Forward End of Molten-Salt Loop as Assembled Without Water Jacket.

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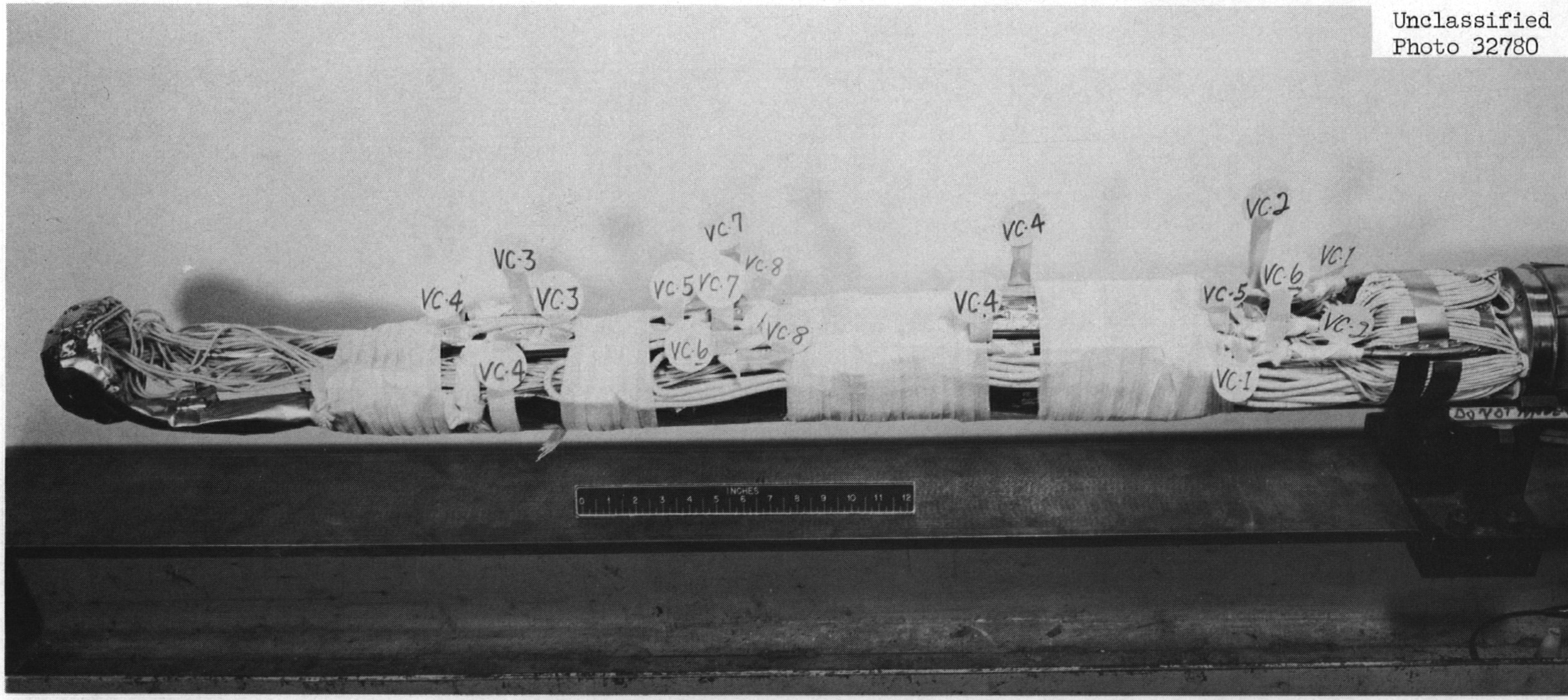

Fig. 55. Overall View of Molten-Salt Loop Assembly Without Water Jacket.

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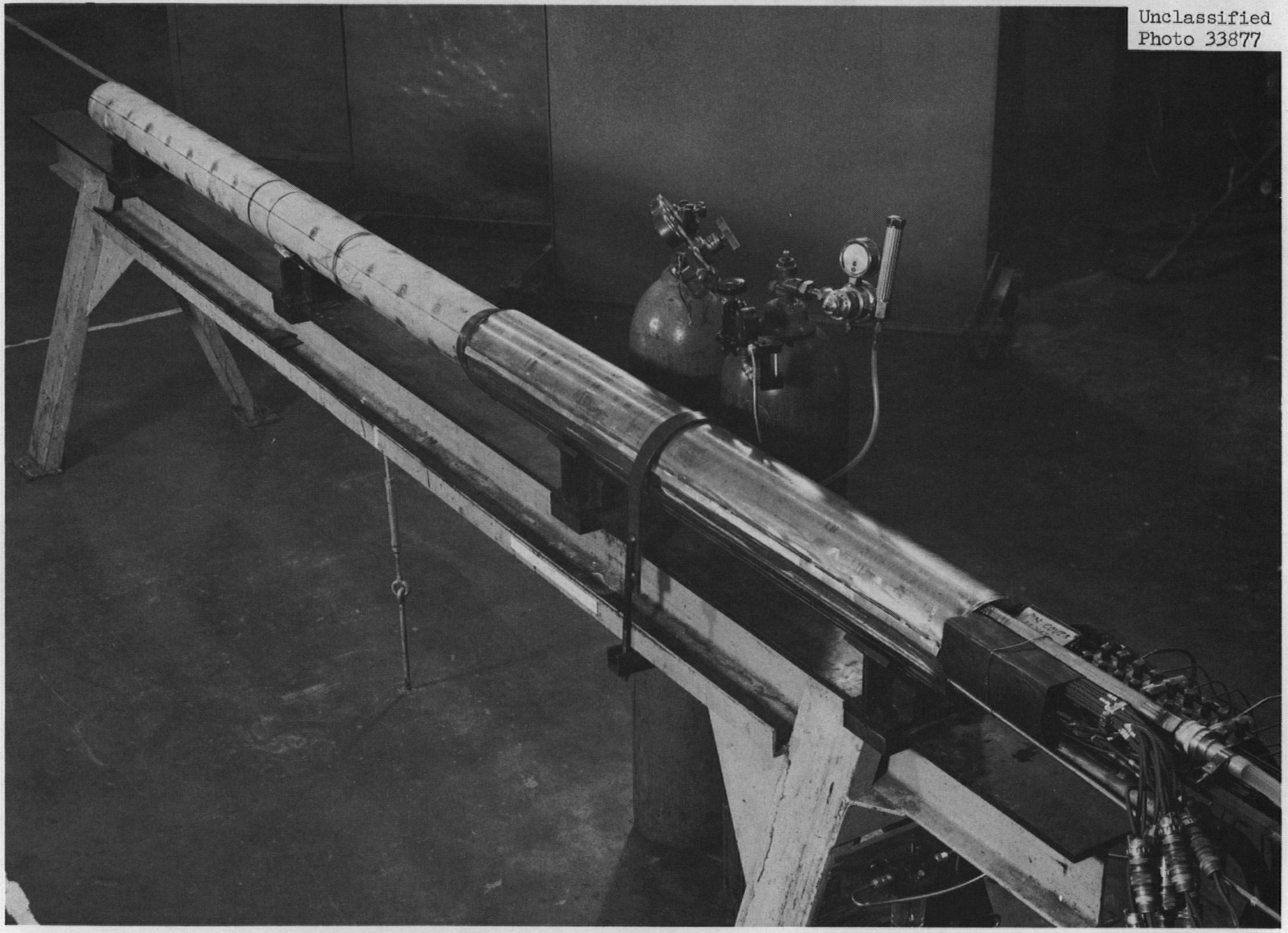

Fig. 56. Completed Molten-Salt Loop on Assembly Fixture. The outer surface configurations of beam hole irradiation assemblies for molten-salt capsules and fueled-graphite capsules are identical except for details of coolant and instrument lines at the rear.

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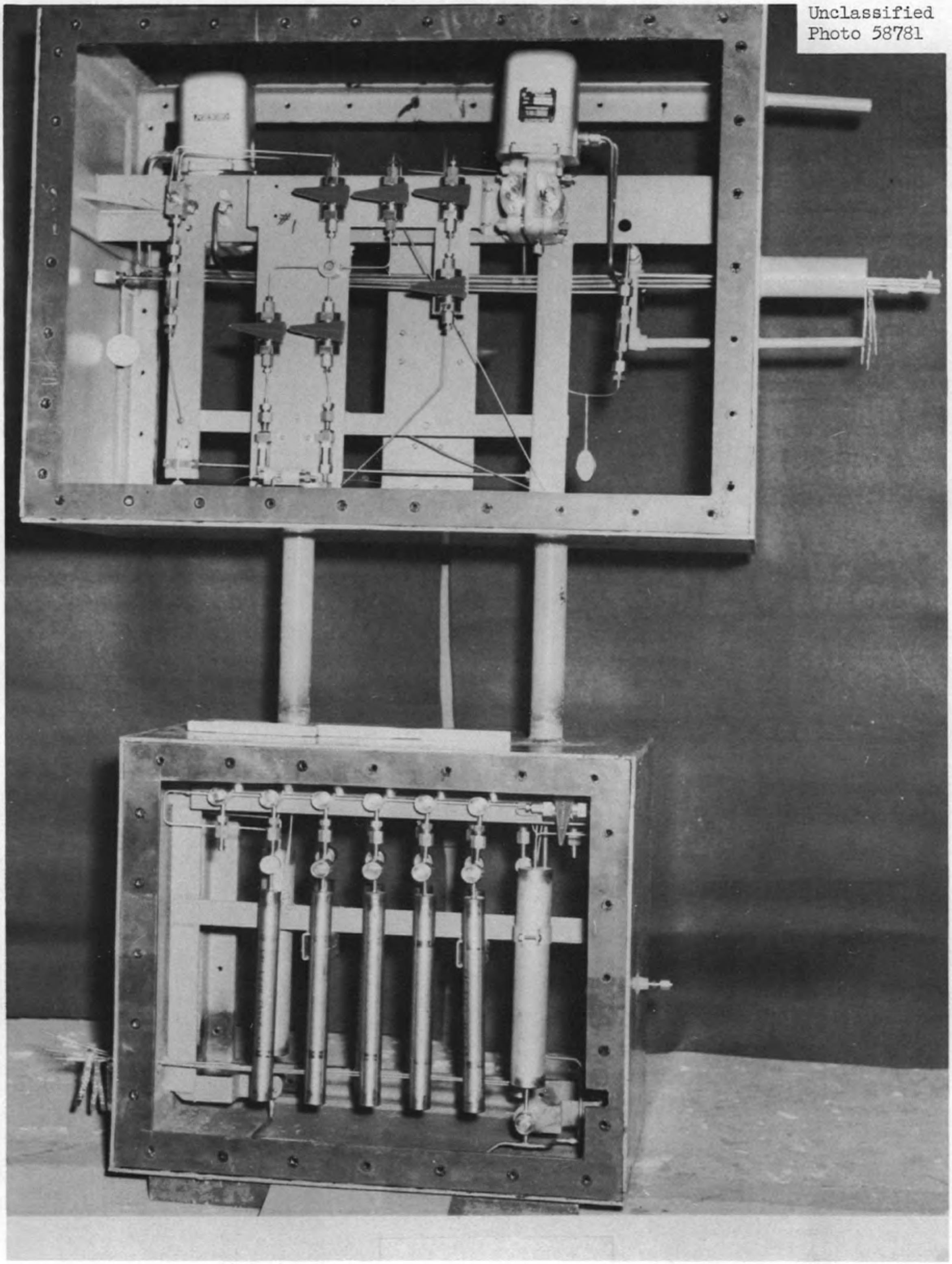

Fig. 57. Sampling Station for Removal of Large Bottles of Radioactive Gas for Chemical Analysis.

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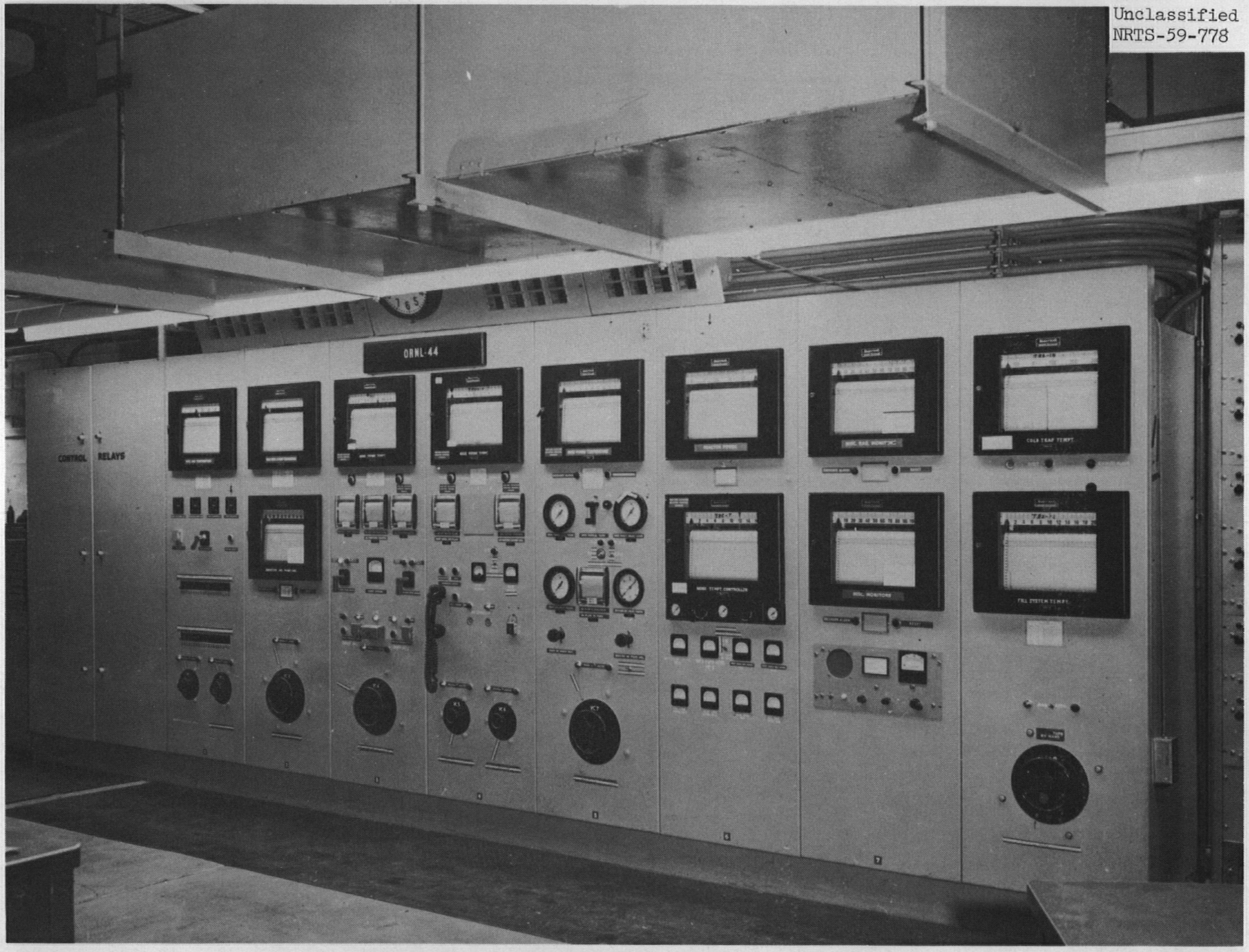

Fig. 58. Instrument Panel for MTR Facility.

Molten-Salt Capsules

Recently the MTR facility has been used for irradiation of molten-salt capsules to determine the chemical compatibility of graphite with the salt in INOR-8 containers. From four to six capsules, each 1/2 to 1 in. in diameter, can be irradiated in a vessel that is sodium-filled for convenience in heat removal. The sodium also affords temperature stability and a bath in which temperature measurements can be made using thermocouples without attachment to the capsule. One capsule assembly is shown in the photograph of Fig. 59. The sectional view of Fig. 60 shows a capsule in which graphite is kept immersed in liquid fuel during irradiation. Provision is made for purging the capsules with helium to carry gaseous products to a sampling station, where they can be removed for analysis.

Temperature control is achieved by changing the thermal resistance between the axially movable sodium tank and the beam-hole water-jacket liner, which have slightly tapering concentric surfaces, to form a gas gap of variable thickness. The overall assembly, shown in Fig. 61, is movable in the beam hole to utilize the flux gradient for control of the irradiation exposure.

Studies of chemical reactions, such as the formation of small quantities of CF_4, as well as released fission gases, have been made both during irradiation and in postirradiation examination. Molten-salt-fueled capsule irradiations conducted in the MTR facility and described in Table 8 have shown the combinations of salt, fuel, and graphite for the MSRE[36] to be compatible at the reactor design conditions.

A capsule design now under development will provide for recirculation of the purge gas to determine equilibrium concentrations of reaction products. Copper blocks that fit closely around the fuel container replace the NaK vessel. Electrical heaters imbedded in the copper will keep the salt molten during reactor shutdown periods.

Fueled-Graphite Capsules

A second modification of the facility has been made in order to irradiate relatively large specimens of fueled graphite. It was desired to determine the stability of UC_2 fuel in a graphite matrix operating at high temperatures and high power densities. Also studied was the performance of sealed low-permeability cans as devices for retaining fission gases.[37]

An overall view of the assembly for these experiments is shown in Fig. 62. The rig containing the graphite specimen is separate from the beam-hole shield and cooling jacket, so only a relatively simple structure needs to be fabricated for each irradiation. One typical assembly is shown in Fig. 63. Neutron flux control is by movement of the assembly in the beam hole. Independent temperature variation and control are not

Table 8. Molten-Salt-Fuel Irradiation Tests

Test Number	Capsule Description	Number of Capsules	Temperature (°F)	Power Density (w/cm^3)	Total Fission Power (kw)
47-1	Inconel bellows; graphite submerged in fuel under 100 psi	4	1300	200	12
47-2	INOR-8 bellows; graphite submerged in fuel under 100 psi	4	1300	200	12
47-3	Graphite crucible containing fuel and materials specimens	4	1750	200	6
47-4	Submerged graphite cylinder	4	1400	65	4
	Small graphite crucible containing fuel	2	1320, 1650	55, 130	
47-5	Submerged graphite cylinder (two capsules purged)	4	1300	35, 65	2.8
	Graphite specimens impregnated with fuel	2		2, 6[a]	

[a]Power density in w/cm^3 of impregnated graphite.

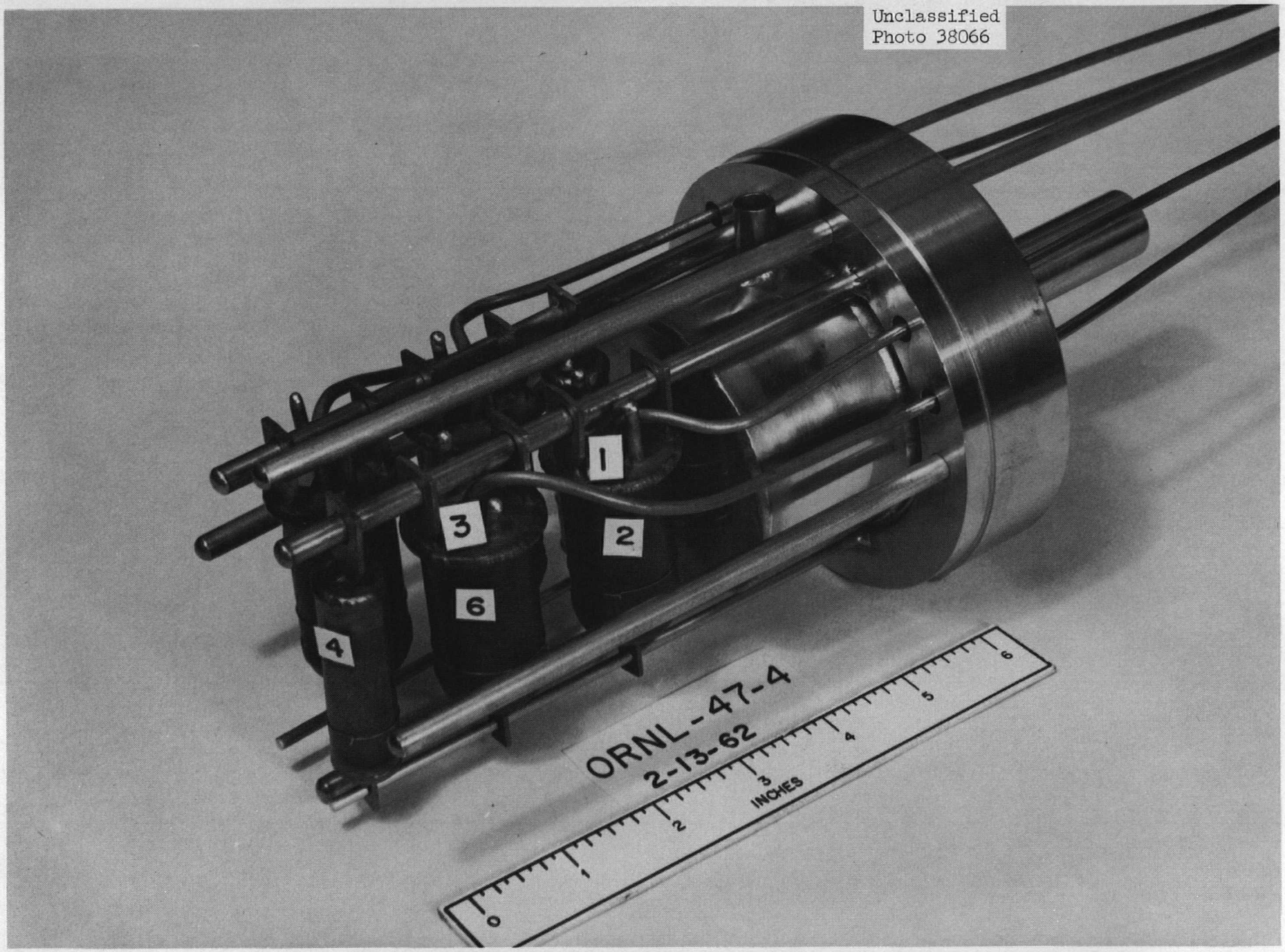

Fig. 59. Assembled Molten-Salt-Fueled Capsules Prior to Installation in Sodium-Filled Can.

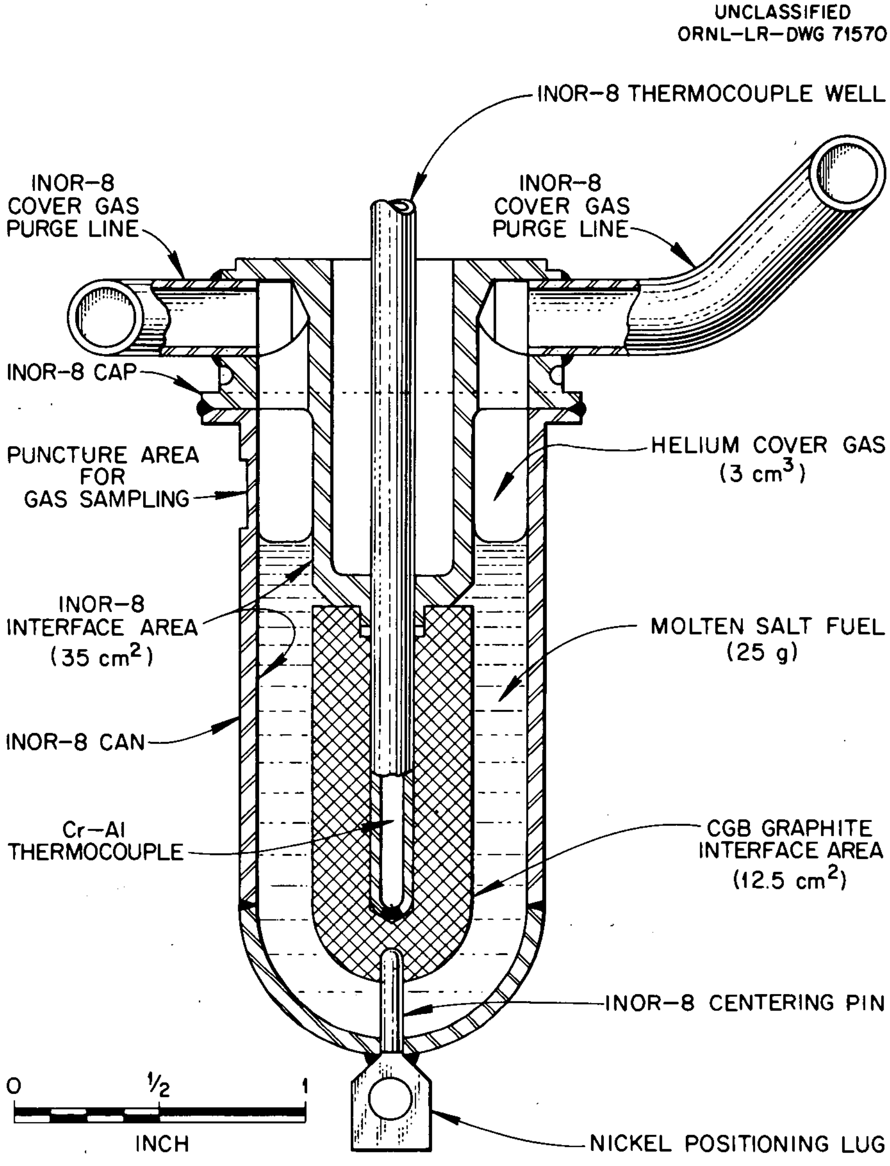

Fig. 60. Purged Capsule Containing Graphite Submerged in Molten-Salt Fuel.

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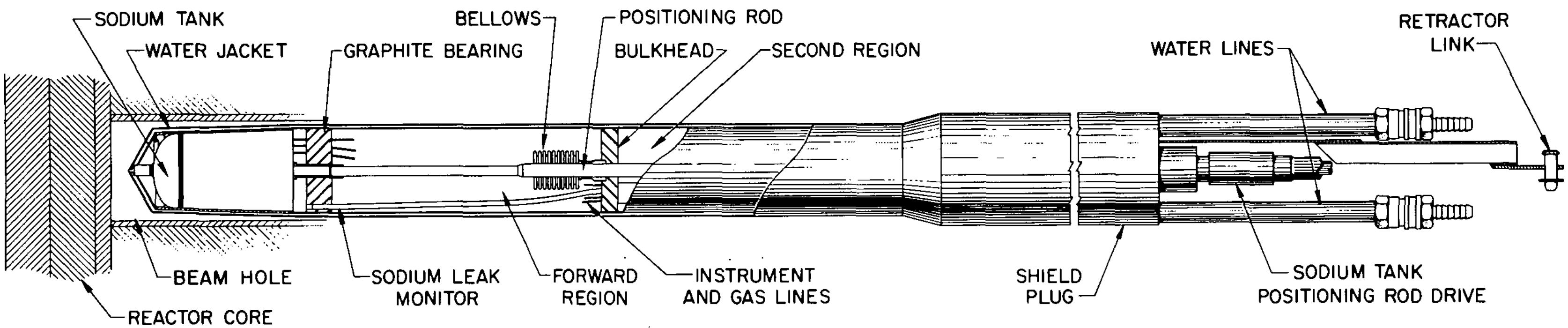

Fig. 61. ORNL-MTR-47-3 Molten-Salt-Fueled Capsule Test Assembly.

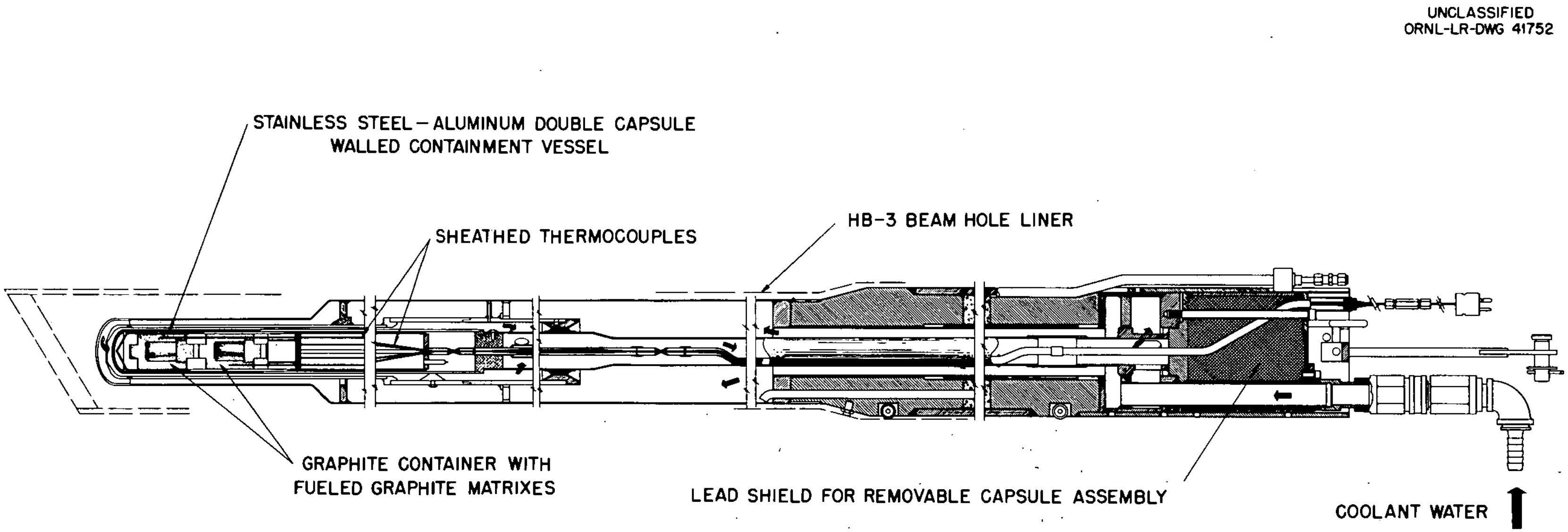

Fig. 62. ORNL-MTR-48 Capsule and Plug Assembly for Advanced GCR Fuel-Element Irradiation Tests.

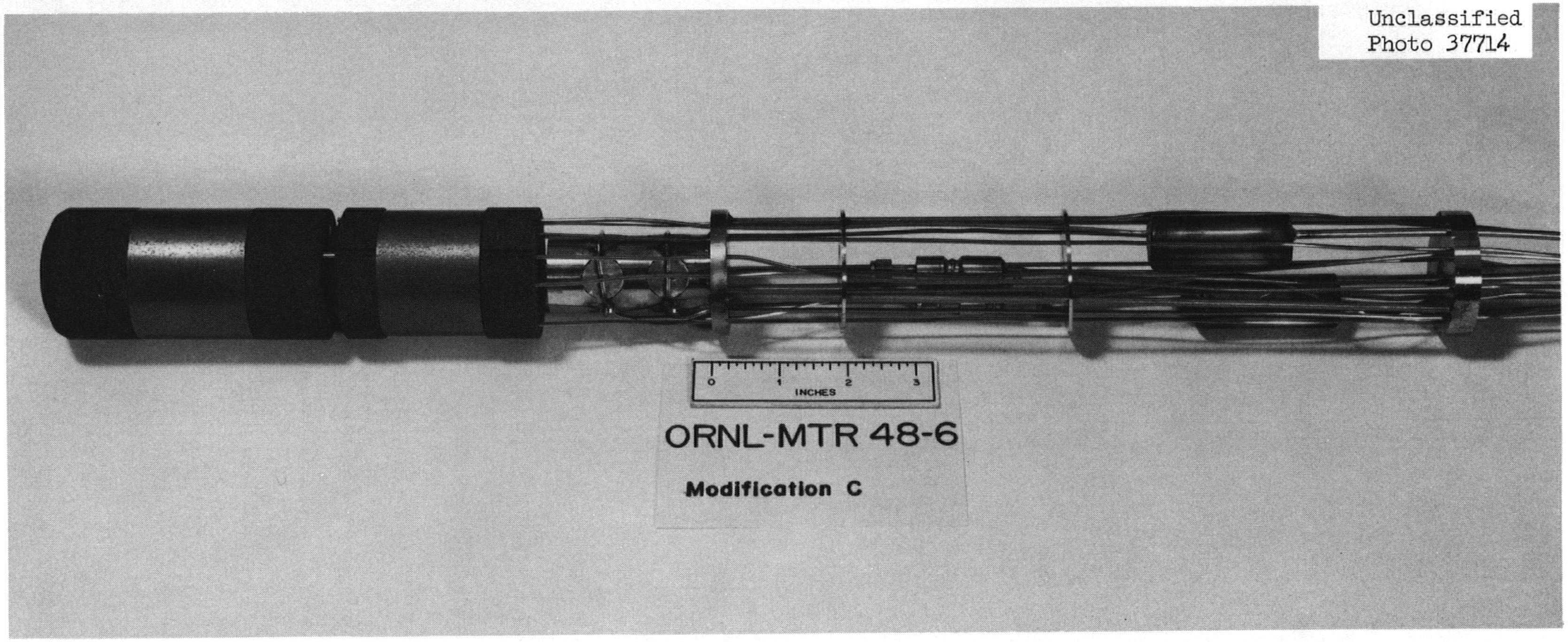

Fig. 63. Assembly for Graphite Matrix Fuel Element and Loose Coated-Particle Irradiation in the MTR Capsule Facility.

provided, although power adjustment made through variation of flux can be used to establish the desired temperature. The fuel chamber can be purged with helium to remove released fission products to a sampling station where small vials of gas can be removed for analysis by gamma-ray spectrometry.

Graphite-matrix fuel elements containing either pyrolytic-carbon-coated or uncoated uranium carbide particles have been irradiated. Several specimens, including containers of loose coated particles, have been irradiated simultaneously in some assemblies. Limited provision has been made for studies of fission-product deposition as it is affected by surface roughness and chemistry. The tests that have been completed are described in Table 9.

Shop Facilities for Capsule and Loop Assembly

The degree of success of any reactor fuel irradiation program is determined in large measure by the capability for fabrication of test assemblies. The equipment must meet very high standards of reliability to achieve safety in test reactor operation and to ensure useful results commensurate with the high costs of the materials irradiated and of the neutrons utilized. Furthermore, close tolerances frequently are necessary to achieve the required precision in temperature measurement and control, in heat removal, determination of flow rates, and other test conditions.

A special shop equipped for assembling capsules and for loop construction is available. This shop is arranged as shown in Fig. 64. It provides for independent assembly of each type of capsule or loop so that several may be in construction simultaneously. Test assemblies manufactured in the shop have varied in size from the small LITR capsules of Fig. 21 to the EGCR instrumented fuel assemblies of Fig. 65, which when completed will be 45 ft long.[38]

Special work areas have been provided that are each designed for critical steps or techniques, such as the preparation of thermocouples, welding, cleaning assemblies, evacuating, and dry box work. Much of the work is highly specialized; for example, welding small tungsten vs rhenium thermocouple junctions, filling capsules with liquid metals, and assembling structures in contact with fuel element materials.

Since thermocouples are used as the primary sensors for most irradiation experiments, considerable attention has been paid to techniques for their manufacture. In general, metallic-sheathed swaged thermocouples have been used. For service up to 1700°F, Chromel-P vs Alumel wires and junctions with MgO insulation and stainless steel sheathing are standard, and the technology is well known. At higher temperatures, tungsten and rhenium, or alloys of these metals, in particular, W–5% Re vs W–26% Re, have been used.[24,39,40] Beryllium oxide insulation sheathed with tantalum

Table 9. Fueled-Graphite Capsules Irradiated in the MTR

Experiment Number	Description	Number of Elements	Surface Temperature (°F)	Central Temperature (°F)	Power Density (w/cm^3)	Total Power (kw)
48-1	UC_2 in graphite matrix encapsulated in permeable graphite	2	1600	3500[a]	280	10
48-2	UC_2 in graphite matrix encapsulated in low-permeability graphite[b]	1	1500	2500[a]	150	3
48-3	UC_2 in graphite matrix encapsulated in low-permeability graphite[b]	1	1500	3500[a]	290	18
48-4	UC_2 in graphite matrix encapsulated in low-permeability graphite[b]	1	1500	3500[a]	280	17
48-5	Pyrolytic-carbon-coated UC_2 particles in graphite encapsulated in permeable graphite[b]	1	1500	2500[a]	150	3
48-6	Pyrolytic-carbon-coated UC_2 particles in graphite encapsulated in permeable graphite[b]	1	1500	2000[c]	60	3
	Loose pyrolytic-carbon-coated UC_2 particles in stainless steel tubes	4		1200[a]	1500	

[a]Calculated.

[b]Purged for fission-gas-release measurement.

[c]Central temperature was measured using an Inconel-sheathed Pt vs Pt–Rh thermocouple. The Inconel was plated with copper to provide a diffusion barrier to prevent carburization.

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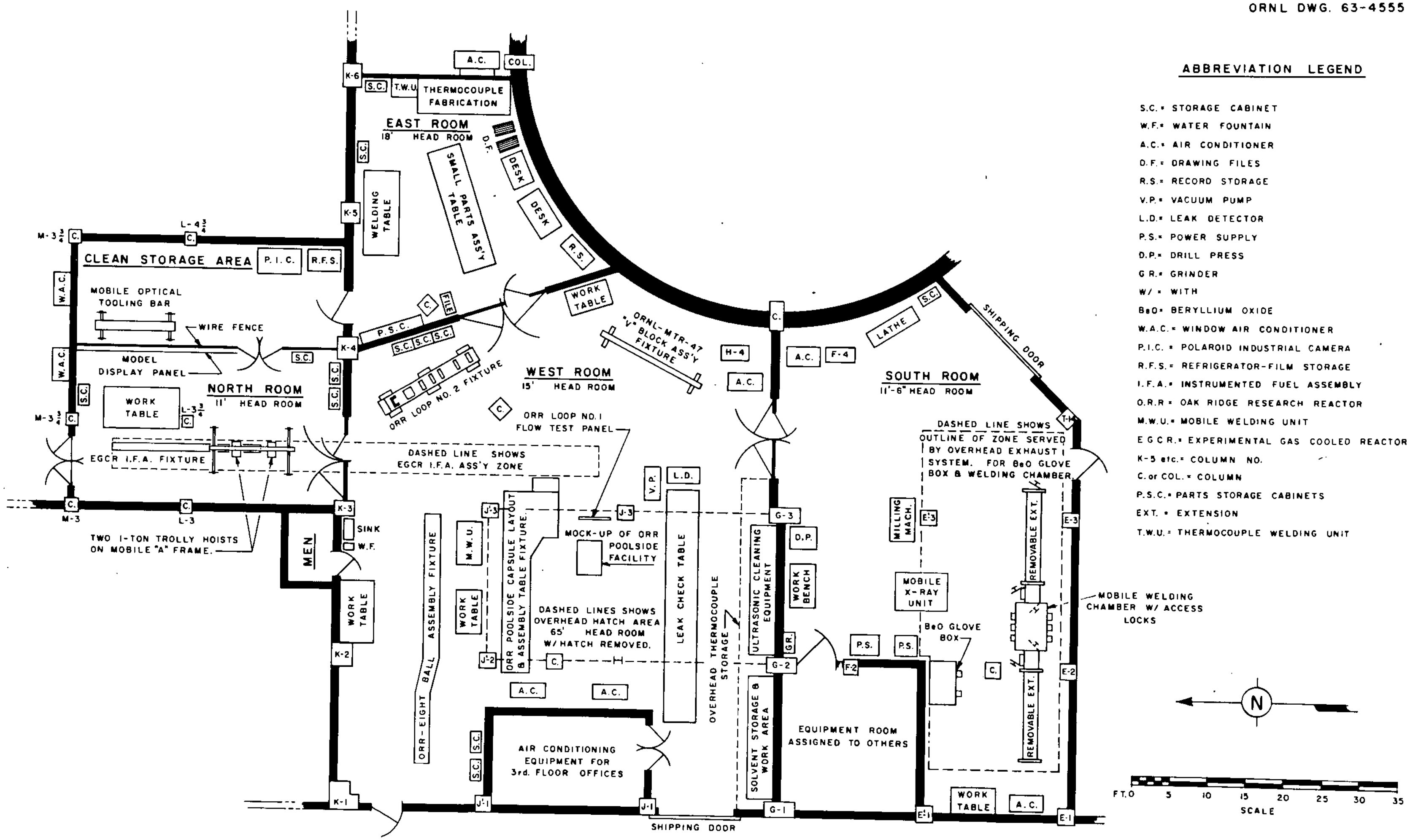

Fig. 64. Plan View of Shop and Assembly Area.

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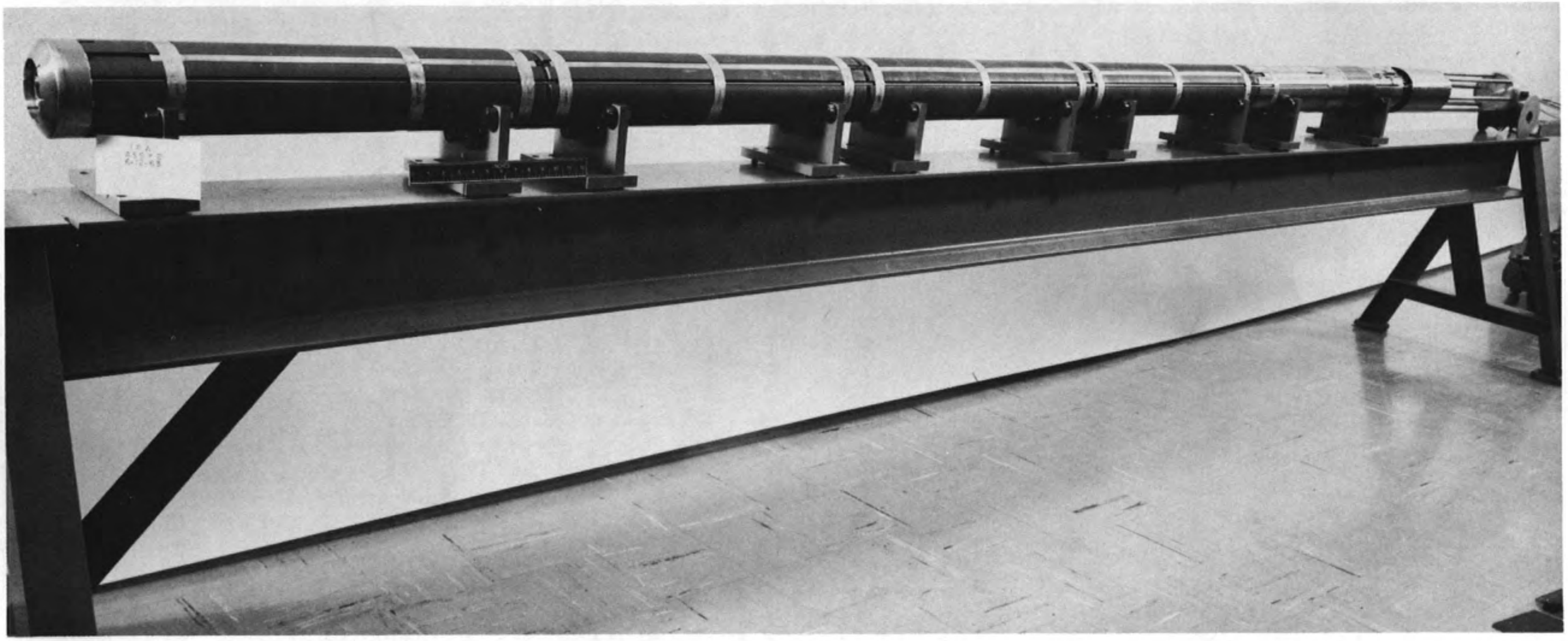

Fig. 65. Instrumented Fuel Assembly for EGCR. This unit (shown ~16 ft in length) is the largest assembled in the shop. Its overall length, including instrument leads and shield, is 45 ft.

has been used extensively at temperatures between 2000 and 4400°F.* For the higher temperature service, insulation with loose fitting beads is preferred. Frequently, the sheath and swaged insulation are removed near the junction and are specially formed for the intended service. Assemblies like that shown in Fig. 66 have given satisfactory service when used with BeO beads and in molybdenum wells for capsule** and loop experiments.*** The junctions are made by inert-arc welding using a miniature torch with semiautomatic equipment and with magnifying optical systems for viewing.

Cleaning equipment for irradiation equipment parts and assemblies includes tools for air blasting with abrasives, an ultrasonic cleaning bath, high-vacuum pumps, and high-temperature furnaces. Conventional solvents and abrasives are also used. Hydrogen furnaces and specialized metallurgical facilities are available but are not part of the assembly shop.

Rigid assembly benches with clamping jigs and fixtures are used to establish the outer configuration of each assembly to ensure a suitable fit in the reactor facility. This is highly important, since test reactor structures are relatively light, and impairment of reactor functions, including control rod action, can result from poor fit up. Separate jigs are provided to check the alignment of equipment, especially where several pieces are to be installed in sequence. Optical tooling is employed to establish the alignment of jigs and fixtures and, at times, to inspect finished parts.

Inspection services utilize dye penetrants, helium leak testing, commercial x-ray, 1,000,000-volt x-ray, x-ray equipment with closed circuit television, isotope irradiation sources, dimensioning tools, including a large surface plate, optical equipment, gas flow metering, and test furnaces. Thermocouple calibration furnaces and associated readout equipment have been provided.

Photographs of specialized shop equipment are shown in Figs. 67 through 74. A highly trained staff of technicians and craftsmen is supervised by a mechanical engineer. Each assembly is built to drawings and specifications following detailed assembly procedures.

Relatively low costs for capsule assemblies are achieved through the use of special tools, careful scheduling of work, including simultaneous construction of several assemblies where possible to better utilize special crafts, and through close supervision of work to minimize rejects. The task engineer for each experimental test rig works closely with the shop supervisor during the assembly of his equipment to ensure its satisfactory performance in the test reactor.

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*See section on "LITR Air-Cooled Capsules."

**See section on "ORR Poolside Capsule Facility."

***See section on "ORR Gas-Cooled Loop No. 1."

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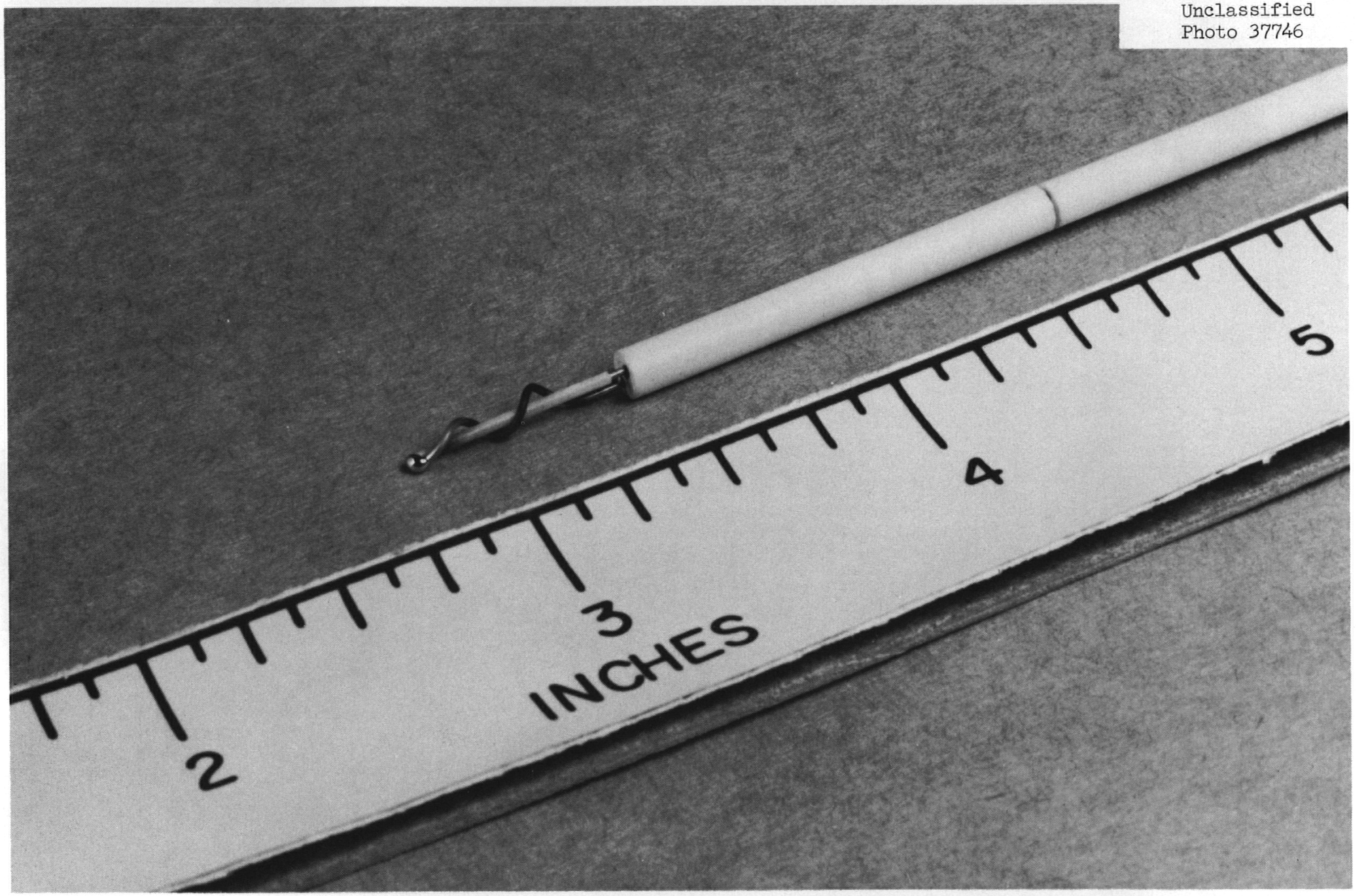

Fig. 66. Tungsten vs Rhenium Thermocouple Assembly with BeO Insulation.

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Fig. 67. Instrument Mechanic Preparing Sheathed Thermocouples for Welding of Insulated Junctions.

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Fig. 68. Welder Making Thermocouple Junctions with Semiautomatic Welding Equipment.

Fig. 69. Closeup of Binocular Microscope and Blasting Gun Used to Prepare Sheathed Thermocouples for Welding Insulated Junctions.

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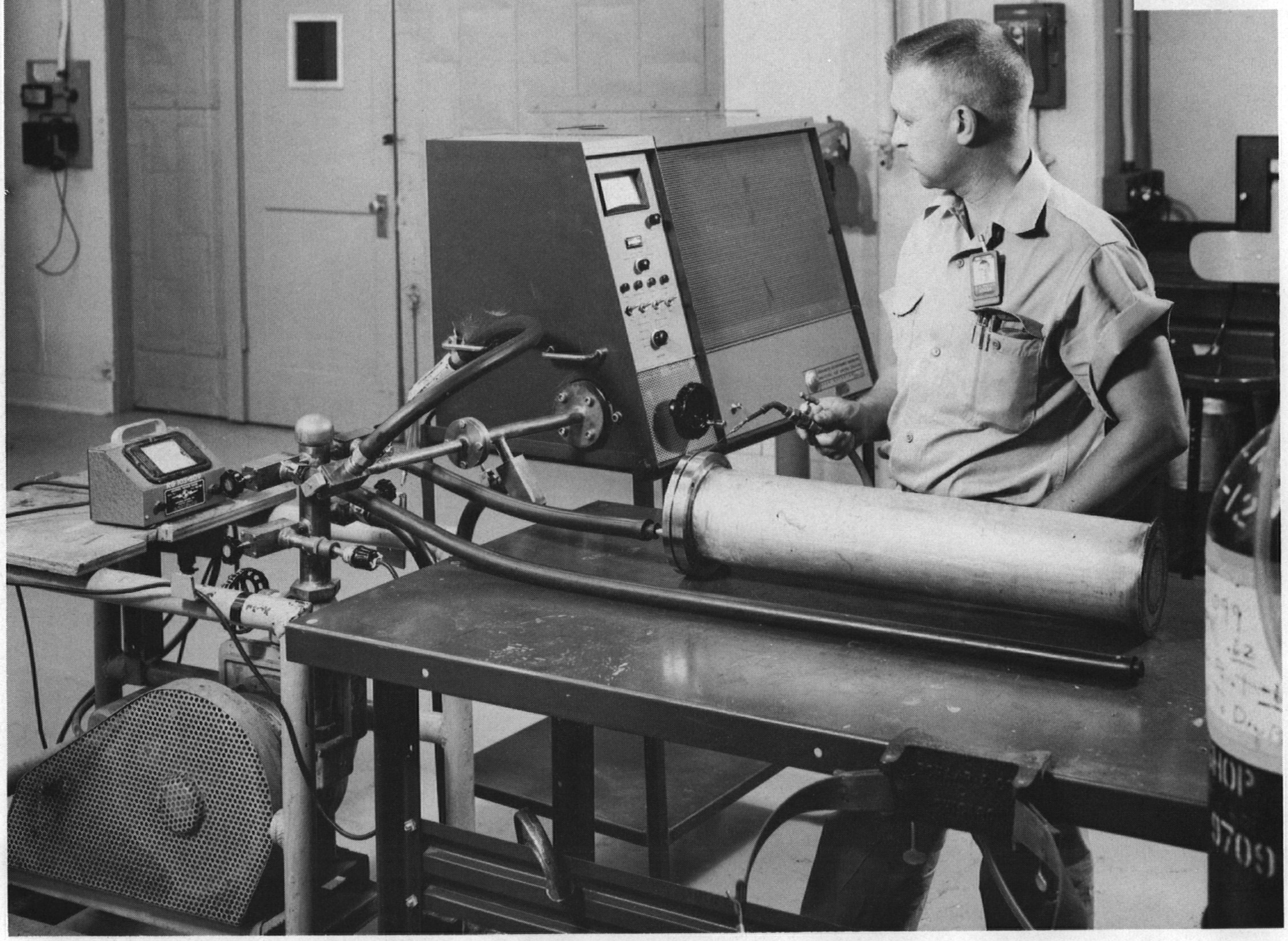

Fig. 70. Helium Leak Checking a Container with Mass Spectrometer-Type Leak Detector.

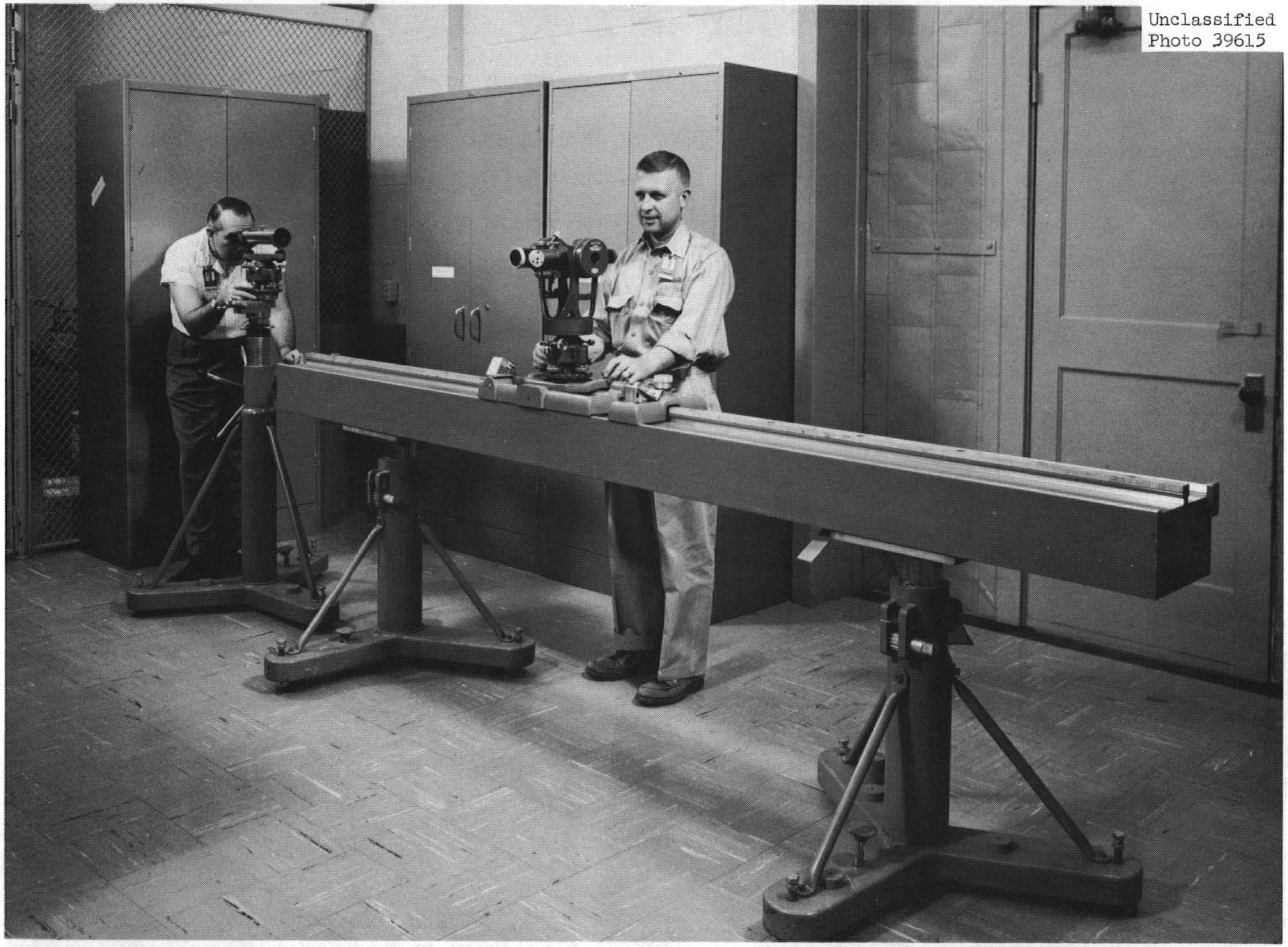

Fig. 71. Brunson Optical Tooling Equipment.

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Photo 38702

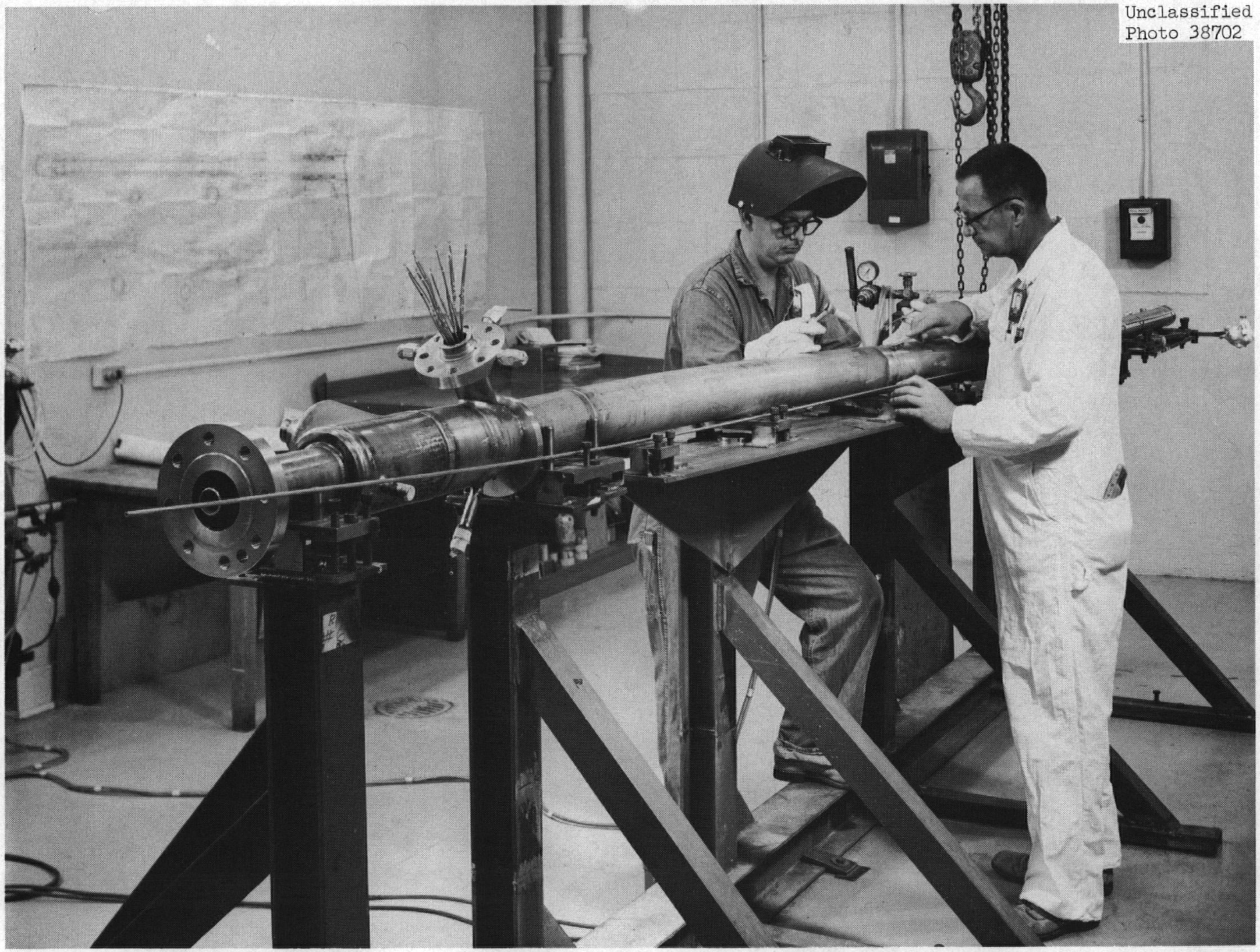

Fig. 72. Loop 1-S In-Pile Section on Assembly Fixture.

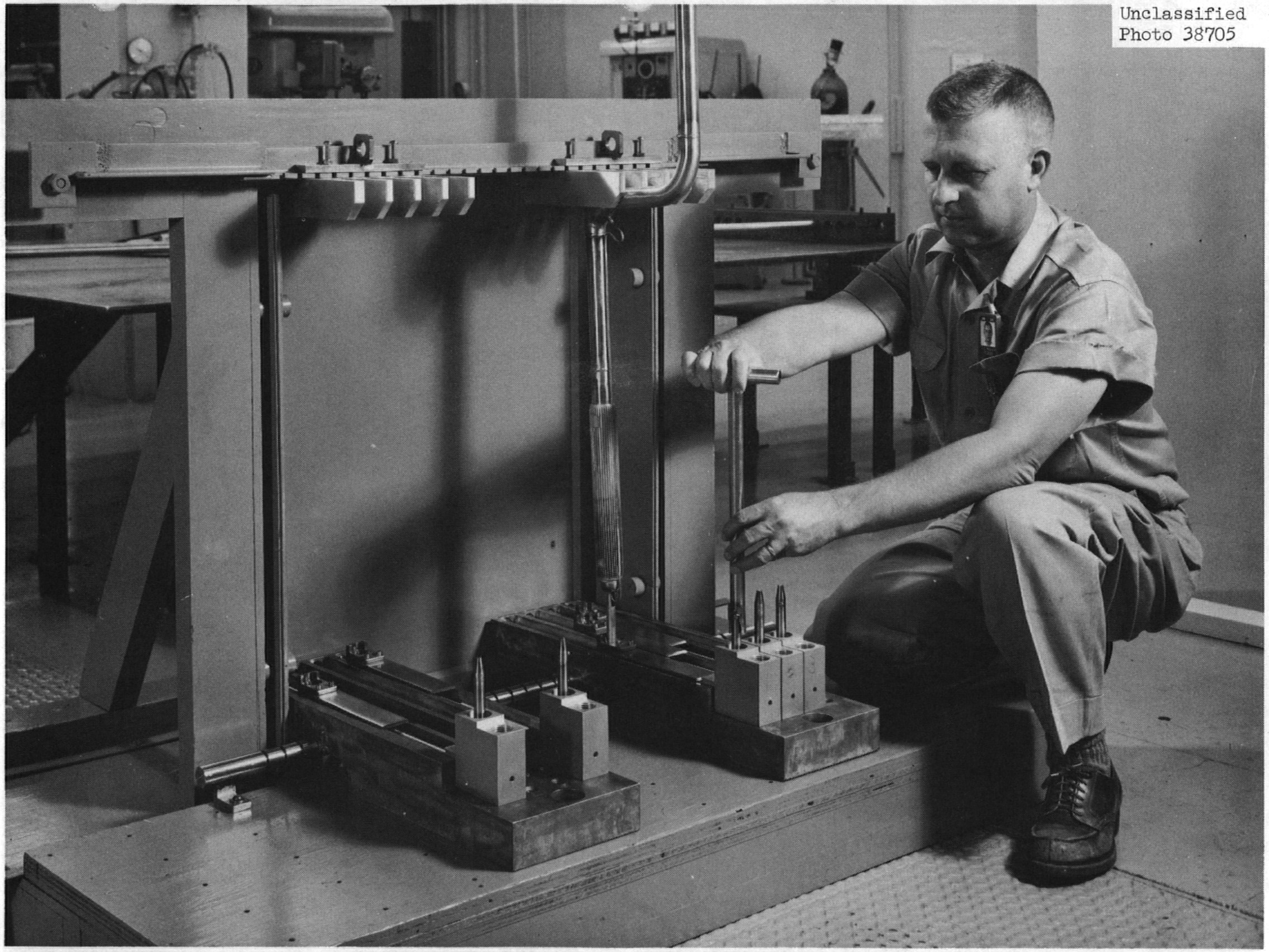

Fig. 73. ORR Poolside Facility Mockup Showing ORR Capsule in Positioning Mechanism Which Duplicates Installation at the Reactor.

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Photo 39650

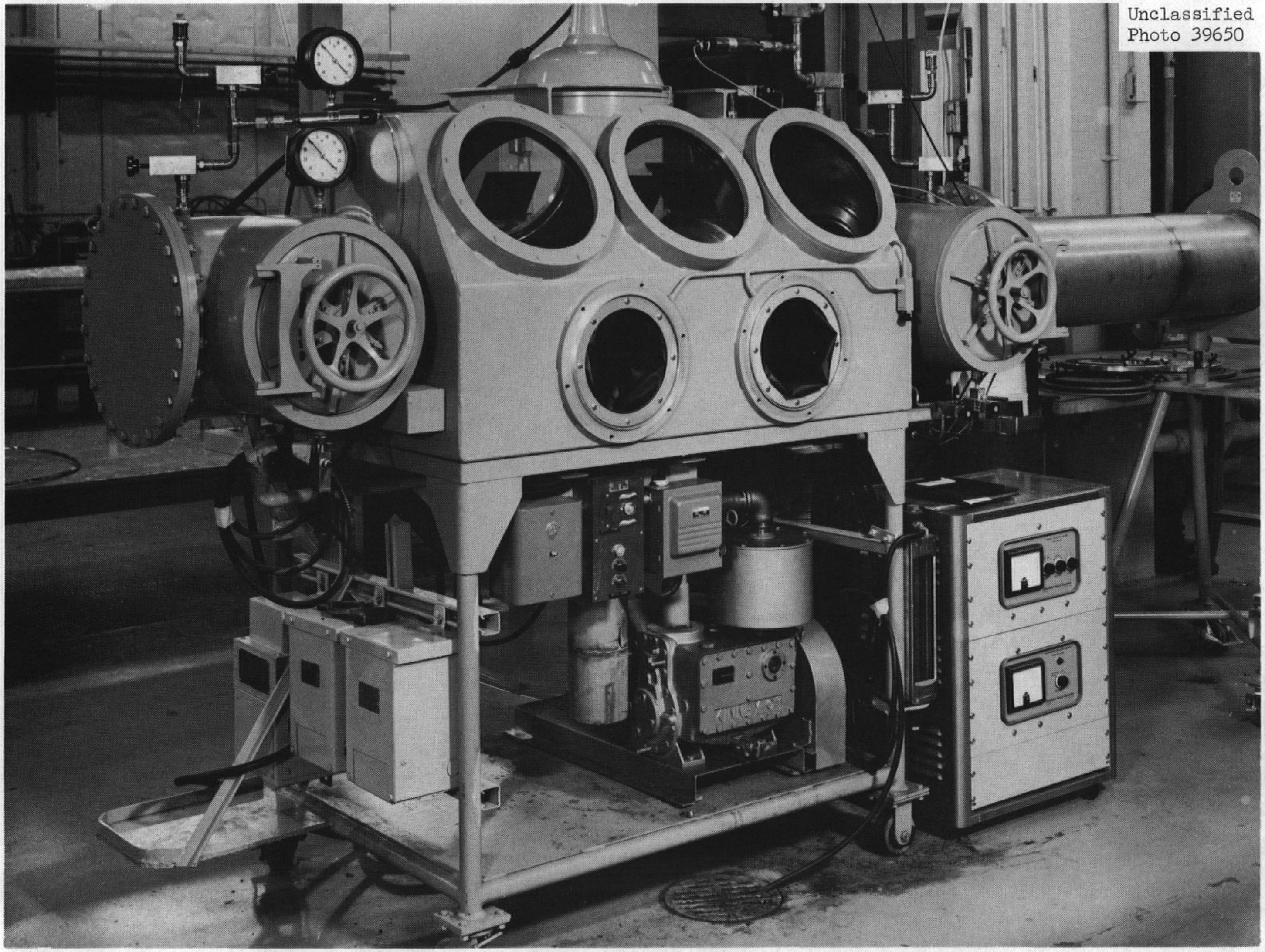

Fig. 74. Blickman Welding Chamber in Assembly Area.

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