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MSRE CAPSULE IRRADIATION EXPERIMENT

ORNL-MTR-47-3

C. A. Brandon
J. A. Conlin

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ABSTRACT

The design and operation of one of a series of molten-salt fuel capsule experiments, ORNL-MTR-47-3, in support of the MSRE is described. The experiment involved the simultaneous irradiation of four capsules containing graphite crucibles into which molten salt fuel and materials' specimens were placed in contact with one another. The capsules were irradiated for a three-month period at fuel power densities in the range of 200 w/cc and temperatures from 790 to 900°C.

INTRODUCTION

The Molten Salt Reactor Experiment is a circulating fused salt fuel reactor which employs a bare graphite moderator in the form of a lattice through which the salt is circulated. The entire core is contained in an INOR-8 vessel which may have a molybdenum internal structure to restrain the graphite. Operating temperatures within the reactor system vary from 680 to 730°C. The irradiation experiment described herein is designed to demonstrate the integrity and compatibility of the MSRE core material under conditions similar to, but more severe than, those of the reactor. One question, in particular that of the possibility of wetting of the graphite by the fuel, was to be studied. Graphite is a porous medium but is not penetrated by the salt fuel because of the non-wetting characteristic of the salt-to-graphite interface. However, if under reactor conditions wetting were to occur permeation of the graphite by the salt fuel is possible and would, if severe, cause serious changes in the reactivity and conversion rates of the reactor. The experiment described in this report is the third in a series.[1-4]

OBJECTIVE

The objective of this experiment is to obtain a measure of the combined effects of radiation, fissioning, and temperature on the properties of graphite reactor structural materials, and fuel in contact with one another under conditions which, in some ways, are more severe than those anticipated in the reactor. Specifically, information is required on the following:

1. the effect, if any, on the wetting of the graphite by the fuel and the penetration of the fuel therein,

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[1] Oak Ridge National Laboratory, "MSRP Semiann. Prog. Rep. Aug. 31, 1961," USAEC Report ORNL-3215, p. 117.

[2] Oak Ridge National Laboratory, "MSRP Semiann. Prog. Rep. Feb. 28, 1961," USAEC Report ORNL-3122, pp. 100-102.

[3] Oak Ridge National Laboratory, "MSRP Qtr. Prog. Rep. April 30, 1960," USAEC Report ORNL-2973, p. 21.

[4] Oak Ridge National Laboratory, "MSRP Qtr. Prog. Rep. Oct. 31, 1959," USAEC Report ORNL-2890, p. 17.

2. the diffusion of fission products into the graphite and the retention therein,
3. the effect of fissioning within the graphite either from fuel penetration or by preimpregnation of fuel into the graphite,
4. the effect of fissioning on the integrity of the graphite surface,
5. the stability and compatibility of the fuel, graphite, and reactor structure materials in contact at operating temperatures and power densities in excess of those of the reactor.

EXPERIMENT DESIGN

Capsule

The four capsules of this experiment were tested in the MTR HB-3 beam hole. All were identical in design but contained different graphites, some of which were preimpregnated with fused salt fuel. The capsules shown in Fig. 1 were horizontal INOR-8 cylinders 1-3/8-in.-OD x 3-1/2-in. long with a 0.055-in. thick wall. Each capsule contained a graphite cylinder with a boat-like cavity hollowed out of the upper half, into which a 5 cc-fused-salt fuel-sample was placed. Materials' specimens of INOR-8, molybdenum, and pyrolytic-carbon were suspended in the fused salt from a graphite blade which rested in slots at the upper ends of the graphite boat. The graphite blade, being of reactor type graphite, National Carbon Co. R-0025, also reached into the salt and was a materials' sample. Two of the graphite cylindrical boats were of National Carbon Co. AGOT, a porous reactor-grade graphite, preimpregnated with salt fuel. The other two boats were of National Carbon Co. R-0025 graphite and were not impregnated. The capsule materials sizes and weights are given in Table 1. Table 2 gives the composition and properties of the molten salt fuel.

The graphite boats were centered in the helium-filled capsules by internal projections in the end caps to provide a helium gap both radial and axial between the graphite and capsule wall. The radial gap of 0.005 in. at operating conditions provided the thermal resistance necessary to permit the operation of the graphite and fuel at temperatures

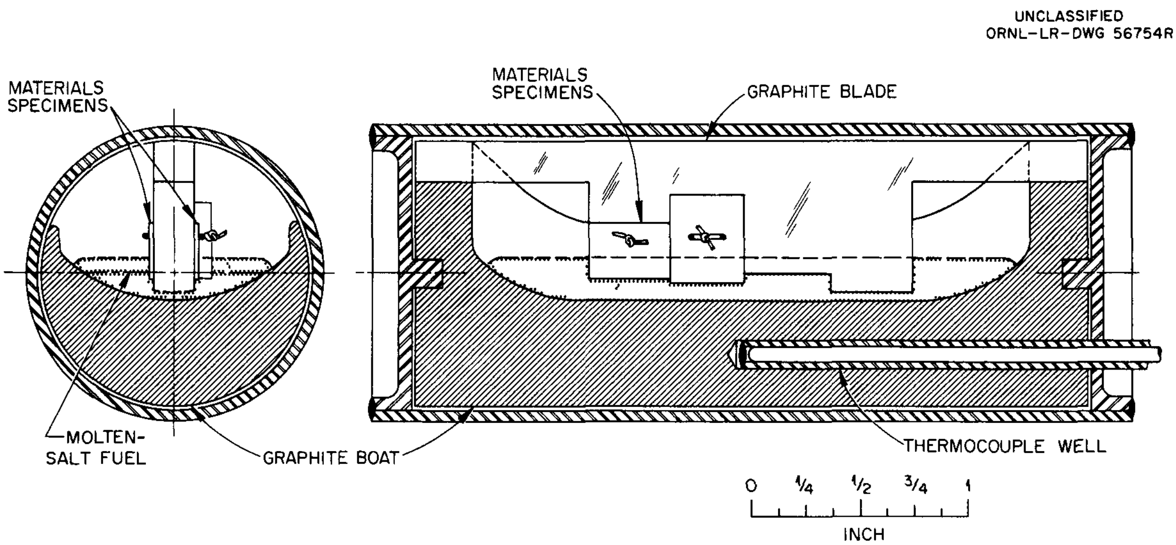


Fig. 1. MSRE Graphite-Fuel Capsule Test ORNL-MTR-47-3.

Table 1. Capsule Data

Capsule Wall	0.005-in.		
Material	INOR-8		
OD	1-3/8-in.		
Length	3-1/2-in.		
End cap thickness	0.062-in.		
Graphite Boat			
Material	AGOT (impregnated) and R-0025 (unimpregnated)		
Length	3.125-in.		
Diameter	1.259-in.		
Graphite Blade			
Material	R-0025		
Length	3.127-in.		
Thickness	0.183-in.		
Specimens			
Material	Molybdenum,	INOR-8,	Pyrolytic-carbon
Length, in.	0.375	0.380	0.370
Height, in.	0.250	0.250	0.250
Thickness, in.	0.020	0.021	0.125
Fuel			
Puddle	11.4 g per capsule		
Impregnated	9 g in graphite boat where applicable		

Table 2. Fused Salt Fuel Properties

Composition		
Component	Mol %	Weight %
LiF	69.5	40.095
BeF_2	23	24.042
ZrF	5	18.064
UF_4 93.5% enriched	1.5	10.409
ThF_4	1	6.850
Physical Properties		
Melting point	450°C	
*Specific heat at 1200°F (650°C)	0.455 cal/g°C	
*Thermal conductivity at 1200°F (650°C)	3.21 Btu/hr/°F·ft	
Density at 1200°F (650°C)	2.48 g/cc	

*Assumed in calculation.

well above that desired for the capsule wall. Each of the capsules was instrumented with a 1/16-in.-dia stainless steel sheathed Chromel-P-Alumel thermocouple inserted in a well of 1/8-in.-dia INOR-8 tubing which penetrated to the midpoint of the graphite boat.

The combined effect of radiation and fissioning, temperature, etc., on the non-wetting characteristic of the salt in contact with graphite were to be established by postirradiation examination of the frozen miniscus at the edge of the salt puddle in the graphite boat and at the point where the graphite blade entered the salt. The strong surface tension of the fuel and its non-wetting properties in contact with graphite result in a large convex miniscus at the edge of a free surface of fuel in contact with graphite. In addition, there was a small (0.020-in.) clearance provided between the bottom of a projection on the graphite blade and the bottom of the salt cavity in the boat. This area under the blade was expected to be void of salt and show a convex salt miniscus for a non-wetting condition. As a further indication of wetting, the non-impregnated graphite specimens were to be examined for penetration of salt into the graphite pores.

The various specimens, INOR-8, molybdenum, and pyrolytic carbon, were included in the capsule for materials compatibility evaluation.

Capsule Assembly Procedure

Prior to assembly, the weights and dimensions of all parts were obtained; see Appendix A. All metal components were then degreased and hydrogen fired. The graphite parts were degassed at 2100°C for two to five hours and sealed in an argon atmosphere. The AGOT boats which were to be impregnated with salt were then placed in a receiver without exposure to air, heated to 1300°F in a vacuum, and impregnated with the fused salt fuel by flooding the receiver with salt at 60 psig for two hours. The excess salt was then drained off and the specimens sealed in a helium atmosphere.

All components, together with the necessary tools and fuel, were placed in a dry box. The fuel was contained in sealed lengths of 3/8-in. copper tubing filled with frozen salt. The covers on the component containers were then loosened, and the dry box evacuated and flushed with helium three times. The purity of the dry box atmosphere was monitored with a tungsten-filament oxygen detector. A noticeable oxide vapor discharge will issue from the filament in an oxygen concentration >1 ppm when the filament is raised to 1200°C after being held at about 750°C for one hour to collect oxide.

All graphite parts were reweighed in the dry box to determine weight changes from degassing and salt impregnation. The molybdenum, INOR-8, and pyrolytic carbon specimens were then attached to the graphite blade with INOR-8 wire, the blade positioned in the boat, and 11.4 g of salt (equivalent to 5 cc at operating temperature) placed in the boat. The copper tubes containing salt were opened with a tubing cutter and lightly crushed with heavy-duty pliers to crush and release the salt. After loading, the boat was inserted into the capsule housing and the end cap welded in place. The welding was done in the helium-filled dry box using an argon shielded arc-welder. Throughout this operation, care was exercised to prevent spilling the salt from the boat which could result in small particles lodging between the graphite and capsule wall.

After welding, the capsules were removed from the dry box and heated above the melting temperature of the salt in an induction-furnace to fuse the salt. In test capsules, it was found that, upon cooling, the salt cracked into a few large pieces, but it was possible to tumble the capsule without particles of salt lodging in the gap between the graphite boats and capsule wall. The irradiation capsules were dye checked, helium leak checked and x-rayed prior to assembly in the experiment. A final x-ray indicated that the salt was located properly within the boats.

Experiment Assembly

The capsules were suspended in a horizontal cylindrical tank filled with sodium as a medium to transmit the fission heat from the capsules to a water jacket. The sodium tank is mounted in the forward end of the water jacket which supports the assembly and is integral with a shield plug at the rear. The external dimensions and radiation shielding match the HB-3 beam hole dimensional and shielding requirements. The assembly is shown in Fig. 2.

The capsule assembly is shown in Figs. 3 and 4. The capsules were arranged in a diamond-array with the axes of both capsules and tank horizontal. The capsules used in the experiment were identified with numbers 3, 8, 15, and 16; see Fig. 3. Capsules numbered 3 and 8, containing the fuel impregnated boats, were positioned in the top and bottom, respectively, while numbers 15 and 16, containing the unimpregnated boats, were positioned on the right and left, respectively, as seen with the observer facing the reactor.

The sodium tank is a 1/8-in.-thick stainless steel tapered-cylinder dimensioned for a small helium-filled gas-gap between it and a matching tapered section of a water jacket which surrounds the experiment. The tank contains a sodium expansion volume, welded to the inside of the rear tank bulkhead, and a dip-tube connects the highest point in the sodium tank to the bottom of the expansion volume. During a heating cycle, the expansion of the sodium forces any gas which may be present in the tank

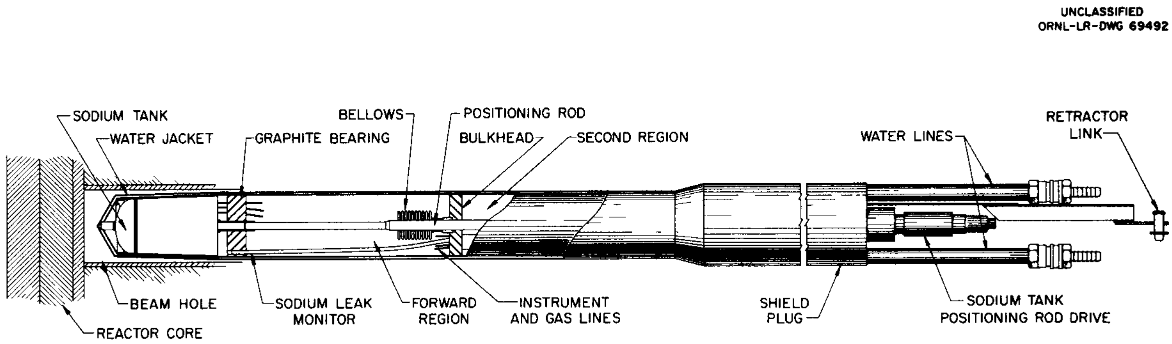


Fig. 2. ORNL-MTR-47-3.

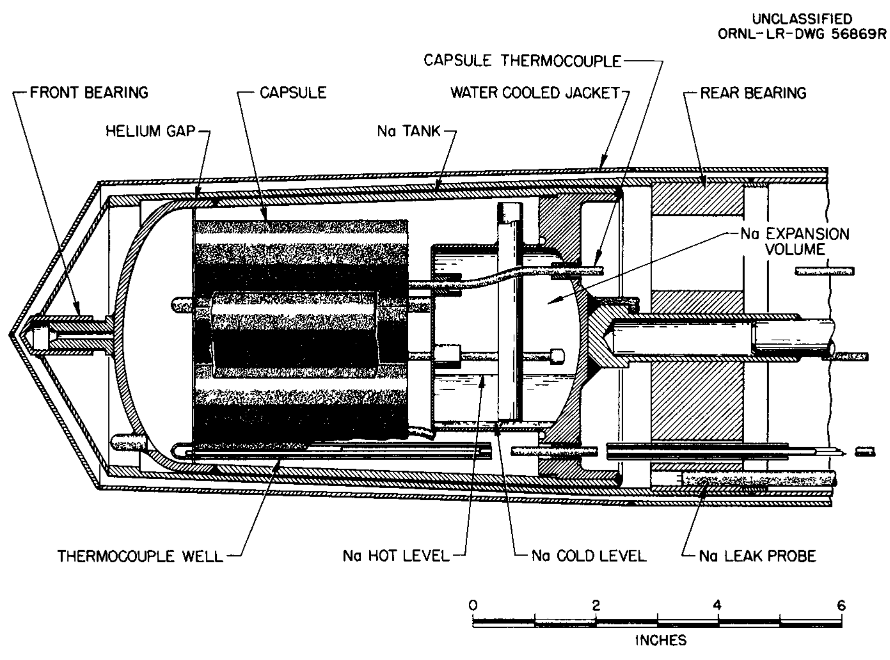


Fig. 3. MSRE Graphite-Fuel Capsule Test; Nose Section.

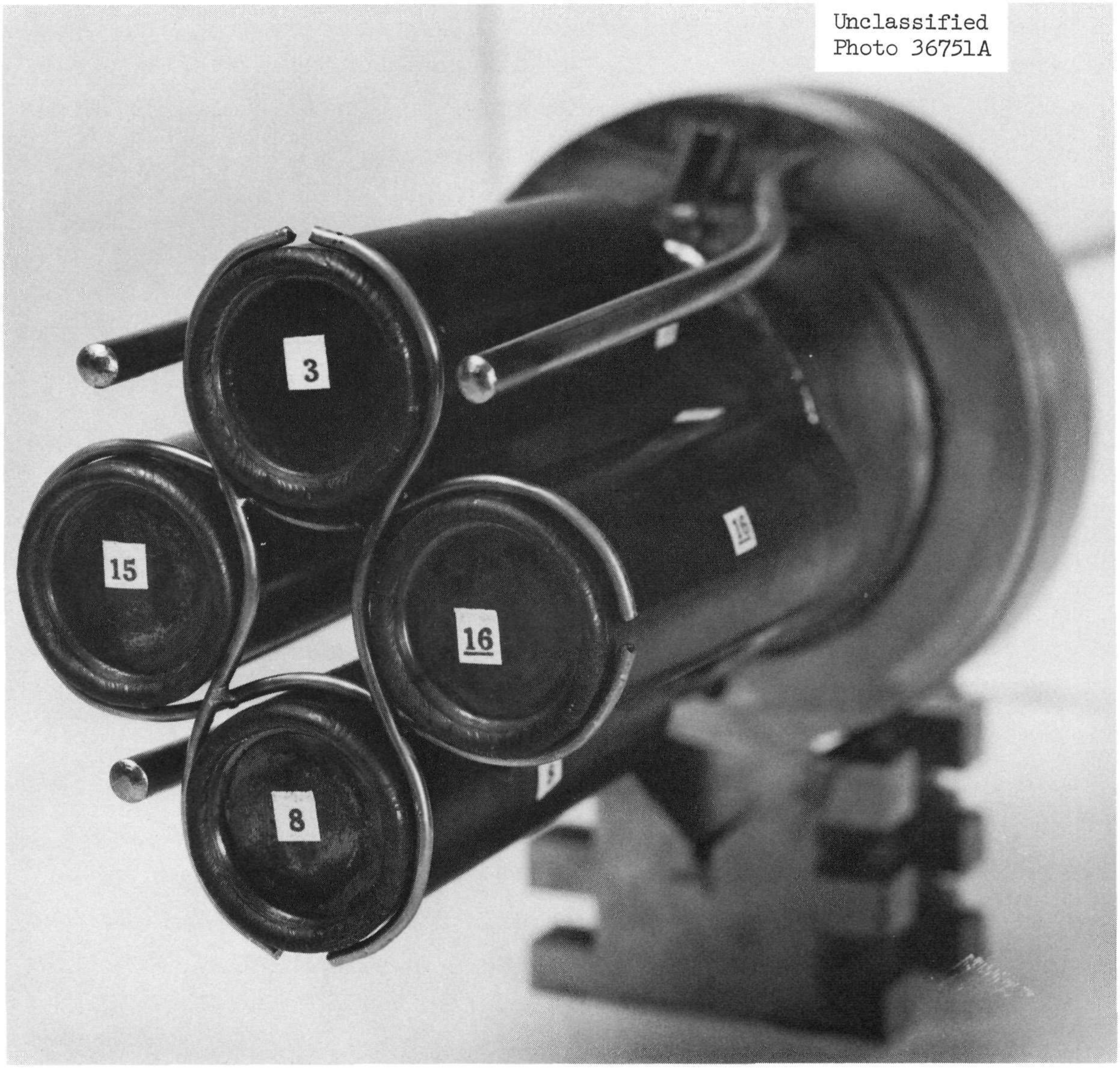


Fig. 4. Capsules Assembled to Sodium Tank Bulkhead.

down through the dip tube into the expansion volume. During a cooling cycle, however, only sodium is drawn out of the bottom of the expansion volume thereby preventing the formation or accumulation of a gas pocket in the vicinity of the capsules. The sodium temperature was monitored by nine 1/16-in.-dia sheathed Chromel-P-Alumel thermocouples in three 1/4-in.-dia tubular thermocouple wells. Both the thermocouples' wells and the wells of the capsule thermocouples penetrate the rear bulkhead of the sodium tank through seal-welded closures.

The sodium tank is mounted concentrically on two bearings in the forward end of the experiment water jacket to maintain a uniform radial gas-gap. One bearing is integral with the inner water jacket nose cone at the forward end, and the other is formed by a graphite block at the rear. The sodium tank is positioned axially by a rod which is threaded into a drive nut at the rear of the experiment. The sodium tank axial position may be varied 5/8-in. by adjustment of this nut; thus changing the gas-gap between its tapered outer surface and that of the water jacket. By this means, the temperature of the capsules may be adjusted by a change in thermal resistance of the gas gap.

The volume enclosed by the stainless steel water jacket is compartmented into two hermetically sealed regions as shown in Fig. 2. The forward region, containing the sodium tank, is sealed by a bulkhead welded to the inner water jacket wall. All lines and sheathed instrument leads entering this region are sealed, by welding or silver brazing, where they pass through the bulkhead. The rod which positions the sodium tank is sealed by a triple-wall stainless steel bellows. The sheathed thermocouples are silver brazed to an insert which, in turn, is welded into the bulkhead. The forward compartment is purged with helium at atmospheric pressure with the effluent passing a radiation detector and then to the reactor stack. An electrical resistance probe serves as a monitor for sodium leakage. The second compartment within the water jacket is similarly sealed. The rear of the water jacket is joined to a concrete-filled shielding plug through which the instrument and service lines are spiraled and through which the sodium tank positioning rod passes. The important dimensions of the sodium tank and water jacket are listed in Table 3.

Table 3. Sodium Tank and Water Jacket Dimensions and Materials

Sodium tank	
Material	347 stainless steel
Maximum diameter, in. OD	4.82
Length, in.	8.5
Wall thickness, in.	1/8
Normal sodium loading, g	900
Axial taper	0.035 in. (radial) per in. of length
Gas-gap range, cold, in.	0.030-0.042
Gas-gap range, hot,* in.	0.007-0.013
Water jacket	
OD, in.	5-1/2
ID, in.	5
Wall thickness, in.	1/16
Water annulus, in.	1/8
Shielding section	
Diameter, in.	6-3/4
Length, in.	55
Shielding material	Barytes concrete
Experiment overall length, in.	170

*Varies with temperature and heat load

The rear of the experiment provides convenient connections for the instrumentation, water, and purge gas lines. A retractor link is mounted at the rear by which the axial position of the experiment in the beam hole may be manually adjusted over a 7-in.-range during operation. This moves the experiment relative to the reactor core, thereby changing the neutron flux to which the experiment is exposed and the heat generation rate within the capsules. The sodium tank positioning-rod drive-nut is extended by means of a flexible shaft to an accessible area to permit manual adjustment while the test is in progress.

Design Operating Conditions

The design operating conditions and temperatures are given in Table 4 and a typical calculated temperature distribution in Fig. 5.

Table 4. Capsule Design Operating Condition

Power density in fuel, w/cm^3	200	
Thermal flux, $w/cm^2 \cdot sec$	2.2	
Gamma heat, w/g	2.5	
Fused salt-to-graphite boat-interface temperature		
Impregnated graphite, °C	980	
Unimpregnated graphite, °C	840	
Capsule heat generation (two capsules)		
	Impregnated	Unimpregnated
Fission heat, w	2094	890
Gamma heat (entire capsule), w	706	663
Total heat rate, w	2800	1553

The temperature distribution was calculated by numerically solving the time-independent heat-diffusion equation with a uniformly distributed source

$$\nabla^2 t + s/k = 0 \quad ,$$

for the two regions, the fuel salt and the graphite crucible; see Appendix B.

The important simplifying assumptions made for the analysis are:

1. The solutions for the two regions were coupled by assuming continuity of the temperature distribution at the salt interface. This effectively assumes any thermal contact resistance at the interface to be negligible. This assumption apparently is valid, but it should be recognized that a thermal resistance equivalent to a 0.001-in. gap filled with helium would result in approximately a 55°C discontinuity.

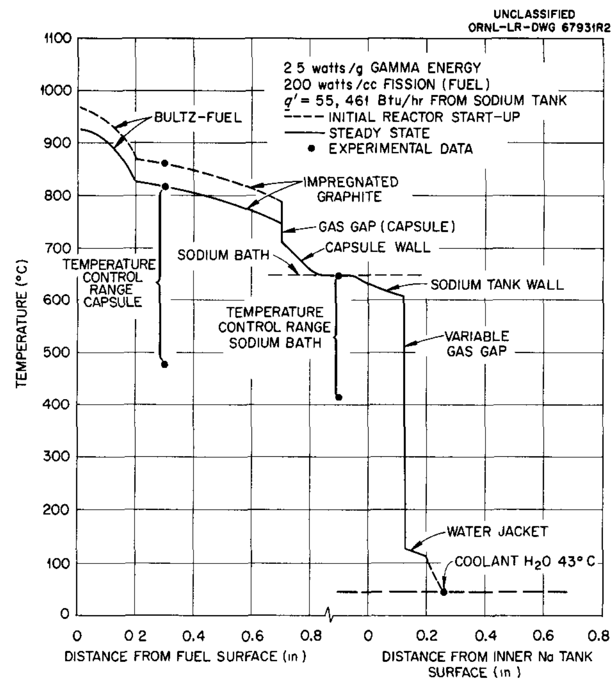


Fig. 5. Typical Temperature Distribution Along Center Plane of MSRE Capsules.

2. The heat transfer by radiation from the salt surface was estimated to be negligible.

3. The presence of the graphite blade and materials specimens was neglected.

4. The problem was reduced to two dimensions by assuming that the end effects were symmetrical and resulted in a finite region in the center where the axial gradient was zero.

The portion of the temperature distribution external to the capsule was obtained by analysis of the system simplified by assuming uniform heat flux from the surface of an equivalent short, cylindrical sodium-tank with insulated ends.

The capsules were designed to operate with an approximate salt-to-graphite interface temperature of 980°C in the case of the impregnated capsules and 840°C for the non-impregnated capsules in a thermal flux of 2.2×10^{13} n/cm^2·sec. The capsules did not reach design temperatures (see section under "Operating History"), in part, because of a discrepancy between the amount of salt actually impregnated in the graphite and that assumed in the calculation.

Instrumentation and Control

The instrumentation and control system has been essentially the same for all experiments of the series. It is shown schematically in Fig. 6. Temperatures are monitored by 1/8-in. stainless steel-sheathed Chromel-P-Alumel thermocouples.

The integrity of the experiment is monitored by two methods. An electrical resistance probe, previously mentioned, is located immediately behind and at the bottom of the sodium tank. The probe consists of a 1/4-in.-OD sheathed-thermocouple with the two thermocouple wires of the sensing-end exposed and unjoined. Six volts are applied to both wires. A sodium leak would short the wires to ground and transmit a signal to the experiment control panel. The second monitor is a helium purge of 1 scfh to the region of the sodium tank. The effluent passes over an activity monitor to indicate a release of fission products in the event of a combined sodium tank and capsule rupture. The effluent then passes through

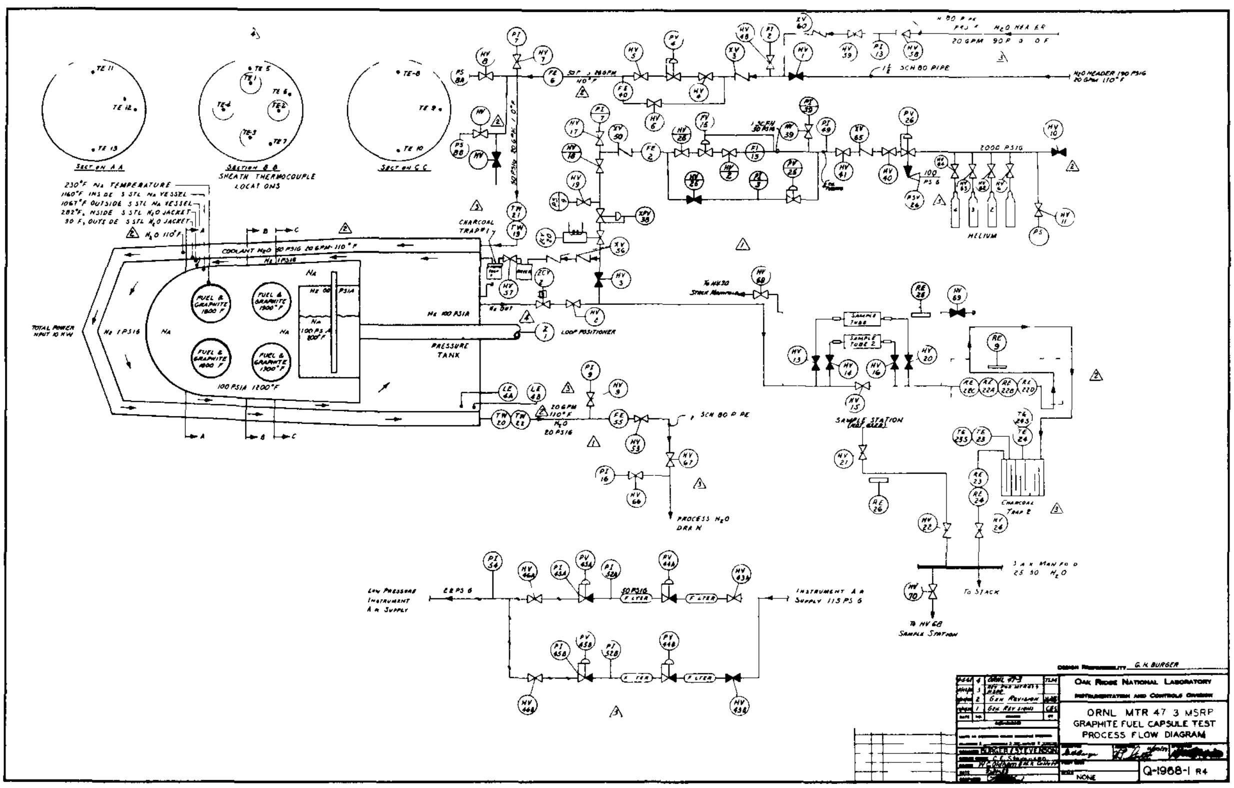

PRESSURE TANK
TOTAL POWER INPUT 10 KW
LOOP POSITIONER
CHARCOAL TRAP
HELIUM
SAMPLE STATION
PROCESS H_2O DRAIN
To STACK
To HV 68 SAMPLE STATION
G. H. BURGER
OAK RIDGE NATIONAL LABORATORY
ORNL MTR 47 3 MSRP
GRAPHITE FUEL CAPSULE TEST
PROCESS FLOW DIAGRAM
NONE
Q-1968-1 R4

Fig. 6.

a charcoal holdup trap and to the reactor offgas system. The purge also is monitored for flow and pressure. A rise in pressure would indicate a plugged purge line or a leak in the experiment water jacket into the region of the sodium tank.

In addition to the experiment temperatures, the coolant water pressure temperature and flow, normally 20 gpm, are also recorded. The normal operating condition and the alarm and control settings are listed in Table 5.

Table 5. Alarm and Control Action

Parameter	Normal	Alarm	Control Action	At Setting
Capsule temperature	700-850°C	None	None	----
Sodium temperature	650°C	700°C	Jr. Scram	730°C
Water pressure	100 psig	<40 psig	None	----
		>125 psig	None	----
Water flow	20 gpm	<15 gpm	Jr. Scram	10 gpm
Helium purge pressure	2 psig	>5 psig	None	----
Helium supply pressure	200-2000 psig	<200 psig	None	----
Purge gas activity	Background	None	Jr. Scram	15 mr/hr
Purge gas activity to MTR offgas	Background	>20 mc/hr	None	----
Sodium leak detector	----	None	Jr. Scram	----
Loss instrument power	----	None	Jr. Scram	----
Loss instrument air pressure	22 psig	<17.5 psig	None	----

OPERATING PROCEDURE

During the initial reactor startup, the experiment is set in the fully retracted position in the beam hole with the helium gap between the sodium tank and water jacket adjusted to the midposition. After the reactor has reached full power, the experiment is inserted in the beam hole and the helium gap adjusted until the design operating conditions are reached. The beam hole position adjustment provides a variation in power of approximately 2.4 from fully-inserted to fully-retracted. Adjustment of the helium gap provides a range of temperature control, in this case 110°C, dependent on the total heat generation of the experiment. The higher heat fluxes provide a greater temperature drop across a given gap and, hence, result in a larger temperature variation over the available gap adjustment. The effective available change in gap is, depending upon operating conditions, in the order of only 0.004 to 0.005-in. As the gap is increased and the temperature rises, the sodium tank expands, nominally 0.004-in./100°F, thereby reducing the gap. The adjustments are made by first inserting the experiment in the beam hole until the estimated temperature difference between capsules and sodium are achieved as an indication of the power generation. The gap is then adjusted until the design temperatures are reached.

Operation

The experiment was inserted in the reactor on May 6, 1961, and operated for four reactor cycles through July 7, 1961.

The temperature history of each of the four capsules is summarized in Table 6. The capsules were irradiated for 1594 hours, 95% of which was at full power during the 1912 hour duration of the experiment.

The operational experimental data of primary interest are the maximum salt-graphite interface temperature and maximum salt temperature. These temperatures were determined indirectly by adjusting the calculated temperature distribution to match the capsule thermocouple indications.

The calculated temperature distribution for capsule No. 3, adjusted to agree with a typical measured capsule temperature, local sodium ambient

Table 6. Temperature History of Graphite-Salt-Interfaces in ORNL-MTR-47-3 Capsules

Total irradiation time: 1594 hr

Operating Condition	Temperature Interval (°C)	Time at Temperature (hr)		
		Unimpregnated Graphite	Impregnated Graphite[a]	Impregnated Graphite[a]
Steady state	0-50	318	318	318
	50-750	33	33	27.5
	750-800	803	803	4
	800-850	702	702	0.5
	850-900			601
	900-950			894
	950-1000			11
	Total	1856	1856	1856
Transient		56	56	56

[a]Temperatures differed because of differences in local ambient sodium temperature.

temperature, and cooling water temperature, is given in Fig. 7. Each of the four capsules is associated with a somewhat different temperature distribution because of differences in fuel loading, natural convective currents in the sodium, the neutron flux distribution, etc.

The steady-state time-averaged graphite-to-salt interface temperatures, at the R-0025 graphite blades, are 790°C for the capsules with unimpregnated graphite and 810°C and 902°C in the capsules with the impregnated graphite. These temperatures were obtained by adding a temperature increment determined from the calculated thermal distribution to a capsule temperature from thermocouple measurements. The difference in the temperature between the impregnated graphite capsules is, for the most part, attributable to a difference in the sodium ambient temperature of 55°C between the top and bottom of the sodium tank. The daily average capsule thermocouple and sodium temperatures were obtained by averaging

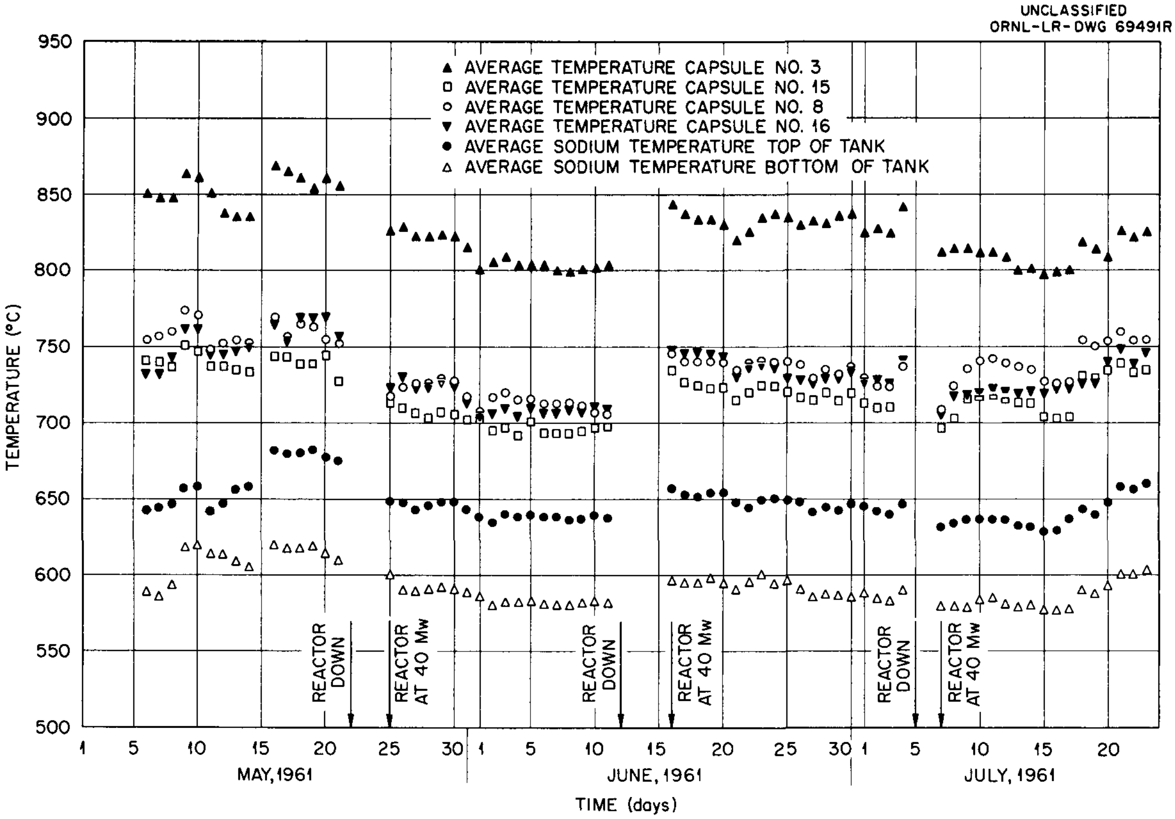


Fig. 7. Measured Temperature History of the ORNL-MTR-48-3 Irradiation Experiment.

data taken during each eight-hour shift and are given in Fig. 7.

Although the experiment was normally operated under steady-state conditions, reactor power fluctuations (scrams, setbacks, etc.) caused thermal transients. During the 56 hours in which the experiment was operating under non-steady-state conditions, 118 temperature transients of 50°F or more were experienced, and the fuel experienced 34 freeze-thaw cycles including the four scheduled reactor shutdowns. Each transient is described in detail in Appendix C by information obtained from the continuous temperature records.

Shortly after the initial startup, a gradual decrease in capsule temperature was observed as shown in Fig. 8. The postirradiation examination indicated that a considerable quantity of salt was lodged in the helium gap between the graphite and the capsule walls. It was apparent that the salt had been deposited by a process of evaporation and condensation. No UF_4 had been transferred. The temperature drop is postulated to be the result of the reduction in the thermal resistance across the gap by the presence of salt. The rate of temperature decrease and the rate of vaporization both decreased as the capsule temperature decreased and the salt came to provide the main path for heat transfer across the gap. Of the 31°C-decrease in the indicated capsule temperature attributable to condensation of salt, 20°C occurred in the first 36 hours of operation.

The operating temperature of the capsules was somewhat below that planned (980°C) at the salt-to-graphite interface of the impregnated capsules. This is, in part, explained by the transfer of salt and, in part, by the fact that the quantity of fuel impregnated in the graphite of these capsules was less than 9.0 g instead of the 17.1 g on which the design was based.

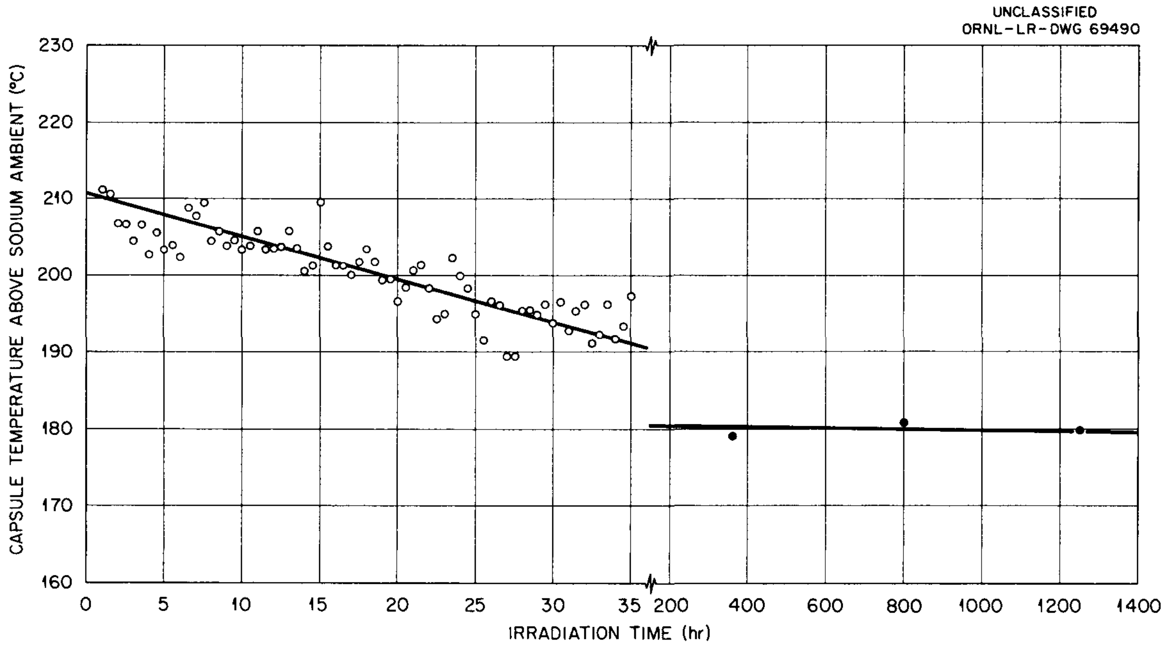


Fig. 8. Initial Capsule Temperature Transient.

ACKNOWLEDGEMENT

We wish to acknowledge all those who participated in the experiment, in particular, W. L. Scott, who directed the design and operation, and for the assistance of R. L. Senn and B. H. Montgomery in the construction of the experiment, F. F. Blankenship in the planning, and R. B. Van Sice, of Phillips Petroleum Company, who was responsible for the operation at the MTR.

APPENDIX A

Preirradiation Measurements

The capsules irradiated in the ORNL-MTR-48-3 experiment were designated as follows:

Number	Location in Sodium Tank
3	Top center
8	Bottom center
15	Left side as viewed from hemispherical end of tank
16	Right side as viewed from hemispherical end of tank

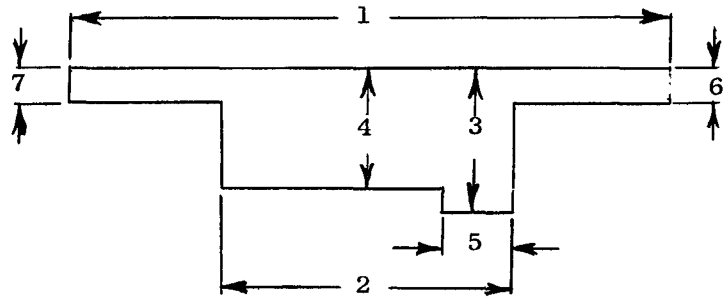
Capsules No. 3 and No. 8 contained the fuel-impregnated graphite boats.

The following tables give the measurements made prior to irradiation. The length measurements of the graphite boats were taken at three locations on the periphery, at the bottom (6 O'clock), and at the sides horizontally opposite at 3 O'clock and 9 O'clock. The graphite boat diameters were measured across the horizontal diameter at three locations, at both ends and the middle.

Three weights are given for the impregnated graphite boats, before impregnation, after impregnation, and after drilling the thermocouple hole. This latter weight represents the "as-installed" condition, since, after impregnation, it was necessary to redrill the thermocouple hole to remove any remaining salt.

The electrical resistance of the graphite boats was measured by passing a current through the boat in the direction of the axis and measuring the voltage across two razor-blades on which the boat rested with the axis perpendicular to the blades. The resistance was determined by comparing the voltage drop across the razor-blades with that of a known resistance through which the same current was passing. The boats were placed on the razor-blades which were one inch apart with the cavity on top and with the end of the boat opposite the thermocouple hole against a fixed stop. The resistance thus measured was only relative, however, since the same equipment was to be used in postirradiation measurements, any appreciable change could be detected.

The graphite blades were measured at the points indicated in the sketch below. The numbers identify the measurements in Table 7.



The materials specimens' length, width, and thickness were measured.

Table 7. ORNL-MTR-47-3 Preirradiation Measurements

	Capsule Number			
	3	8	15	16
Capsule Cylinder				
Material	INOR-8	INOR-8	INOR-8	INOR-8
Identification number	AT-3	AT-10	R-2-R	R-3-L
Graphite boat				
Material	AGOT	AGOT	R-0025	R-0025
Weight, g, before impregnation	66.5008	66.517		
after impregnation	75.581	75.470		
after drilling out T/C hole (as-installed)	74.729	74.621	71.7951	71.6080
Length, in., 3 O'clock	3.12478	3.12466	3.1279	3.1278
6 O'clock	3.12559	3.12530	3.1279	3.1282
9 O'clock	3.12470	3.12462	3.1279	3.1281
Diameter, in., numbered end	1.25805	1.25880	1.2597	1.2598
center	1.25875	1.25960	1.2592	1.2598
opposite end	1.25880	1.25900	1.2592	1.2600
Electrical resistance, ohms, x 10^{-3}	.92	.90	1.025	1.04
Blade				
Identification number	B-12	B-14	B-16	B-18
Material	R-0025	R-0025	R-0025	R-0025
Weight, g	7.1762	7.2001	7.1270	7.1574
Thickness, in.	.5237	.5232	.5227	.5233
Dimensions, in.,				
1	3.1273	3.1268	3.1287	3.1273
2	1.5037	1.5025	1.5010	1.5008
3	.7062	.7062	.7057	.7061
4	.6100	.6089	.6089	.6076
5	.3790	.3772	.3772	.3771
6	.1825	.1830	.1830	.1828
7	.1831	.1823	.1826	.1810

Table 7. Continued

	Capsule Number			
	3	8	15	16
Materials Specimens				
Molybdenum				
Identification number	4	19	3	16
weight, g	.2680	.2860	.2676	.2727
length, in.	.374	.375	.375	.375
width, in.	.250	.251	.251	.250
thickness, in.	.019	.020	.019	.020
INOR-8				
Identification number	4	16	10	11
weight, g.	.2625	.2648	.2652	.2605
length, in.	.375	.385	.379	.384
width, in.	.249	.251	.249	.244
thickness, in.	.021	.021	.021	.021
Pyrolytic carbon				
Identification number	17	20	5	7
weight, g	.6046	.6043	.5270	.5034
length, in.	.3655	.3780	.3670	.3640
width, in.	.3715	.3700	.3672	.368
thickness, in.	.125	.125	.125	.125
Fuel[a]				
Weight, g, impregnated	9.080	8.953		
puddle	11.443	11.403	11.405	11.508

[a]Fuel analysis, wt % = UF_4 10.409

ThF_4 6.850

ZrF 18.604

BeF_2 24.042

LiF 40.095

APPENDIX B

Temperature Distribution Calculations

The steady-state temperature-distribution in the ORNL-MTR-47-3 capsule, Fig. 5, satisfied the time-independent heat-diffusion equation with a uniformly distributed source and constant material properties.

$$\nabla^2 t + s/k = 0 \quad (1)$$

where

$\nabla^2 t$ = differential operation $\sum_{i=1}^{n} \frac{\partial^2}{\partial q_i}$, q_i being coordinates

s = uniform source term, Btu/hr·ft^3

k = thermal conductivity, Btu/hr·ft^2·°F/ft

t = temperature, °F

There are two material regions in the capsule, the fuel salt and the graphite boat-like crucible. The temperature distribution in each satisfies Eq. (1), but the parameter, s/k, is not the same.

Because of the irregularity of the geometry and the complexity of the boundary conditions, the solutions to Eq. (1) for the two regions are obtained numerically by the technique of relaxation.[5,6] To permit a solution by manual calculation, the system is idealized under the simplifying assumptions:

1. The solutions for the two regions are continuous at the interfaces. This effectively assumes any thermal contact resistance at the interface to be negligible. This assumption is apparently valid but lacks positive verification.[7,8] It should be noted that a thermal resistance equivalent to a 0.001-in. helium-filled gap would cause a discontinuity of 100°F.

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[5] W. E. Milne, p. 119 in Numerical Solutions of Differential Equations, Wiley & Sons, Inc., New York, 1953.

[6] P. N. Schneider, p. 150 in Conduction Heat Transfer, Addison-Wesley, Reading, Mass., 1955.

[7] R. N. Lyon, p. 207 in Liquid-Metals Handbook, AEC and Dept. of the Navy, 2nd ed., Washington, D.C., 1952.

[8] W. H. McAdams, Heat Transmission, McGraw-Hill, 3rd ed., New York, 1954.

2. Heat transfer by radiation from the salt surface was estimated to be negligible.

3. The presence of the R-0025 graphite blade and materials specimens was neglected as was the thermocouple well.

4. The problem was reduced to two dimensions by assuming that the end effects were symmetrical and resulted in a finite region in the center where the axial gradient was zero.

5. The material properties were assumed constant at average values.

6. The power generation rates were assumed uniform and constant.

7. The geometry was assumed regular with constant gas-gaps and wall thicknesses.

8. The sodium temperature was assumed constant.

9. The rate mechanism of the natural convection heat transfer to the sodium was assumed to be insensitive to position.

Fuel Salt Region

The simplified geometry of the fuel salt region, shown in Fig. 9, employs a rectangular coordinate system for which the two-dimensional differential equation is:

$$\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} = \frac{s}{k} = 0 \quad . \tag{2}$$

Using approximations to the partial derivatives,[5] the finite difference equation corresponding to the differential equation is:

$$t_1 + t_3 + t_2 \left(\frac{\Delta x}{\Delta y}\right)^2 + t_4 \left(\frac{\Delta x}{\Delta y}\right)^2 - 2\left[1 + \left(\frac{\Delta x}{\Delta y}\right)^2\right] t_o + \frac{s\,\Delta x^2}{k} = 0 \quad . \tag{3}$$

The indices refer to the relaxation pattern indicated for the internal nodes. The facts that nodal patterns are reflected across lines of symmetry, zero normal derivatives, and that the influence of one node upon another is inversely proportional to the distance between them are used to adapt Eq. (3) for irregular relaxation patterns at the boundaries. With the material properties indicated, the difference equation, for the nodal grid selected is:

$$t_1 + t_3 + 6.25\ t_2 + 6.25\ t_4 - 14.50\ t_8 + 183 = 0 \quad . \tag{4}$$

The applicable boundary conditions used in the solution are:

B.C. 1: $\frac{\partial t}{\partial x}(0, y) = 0$, (5)

B.C. 2: $\frac{\partial t}{\partial y}(x, 0.2) = 0$,

B.C. 3: 5 (x, y) = Const = 1800°F (along curved interface with graphite region) .

The first boundary condition derives from the assumed symmetry about the vertical center line. The second boundary condition derives from the estimate of heat transfer from the fuel surface. Neglecting natural convection and conduction across the helium-filled region, the heat transfer by radiation is, assuming infinite parallel planes,

$$q = 0.173\ A \left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right]\left[\frac{1}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1}\right] \qquad (6)$$

q = 194 Btu/hr or ~5% of ~1 kw generated.

Where

A = surface area of molten salt, 0.0208 ft^2

T_1 = average surface temperature of the molten salt, 2360°R

T_2 = average surface temperature of INOR-8 can, ~1400°R

ϵ_1 = emissivity of molten surface, ϵ_1 = 0.4 (Ref. 8)

ϵ_2 = emissivity of INOR-8 surface, ϵ_1 = 0.5 .

The third boundary condition was selected to yield, by trial and error, the maximum temperature desired. The choice of a constant temperature at the graphite-salt is reasonable, consistent with the high thermal conductivity of the graphite. The final results of the relaxation procedure are given in Fig. 9.

Graphite Crucible Region

The simplified geometry of the graphite region is shown in Fig. 10. The region is divided into curvi-linear rectangles and the difference equations are obtained by application of the principle of the Conservation of Energy to each node.[6] The network was made rectangular for convenience in matching the 1800°F isotherm at the salt interface.

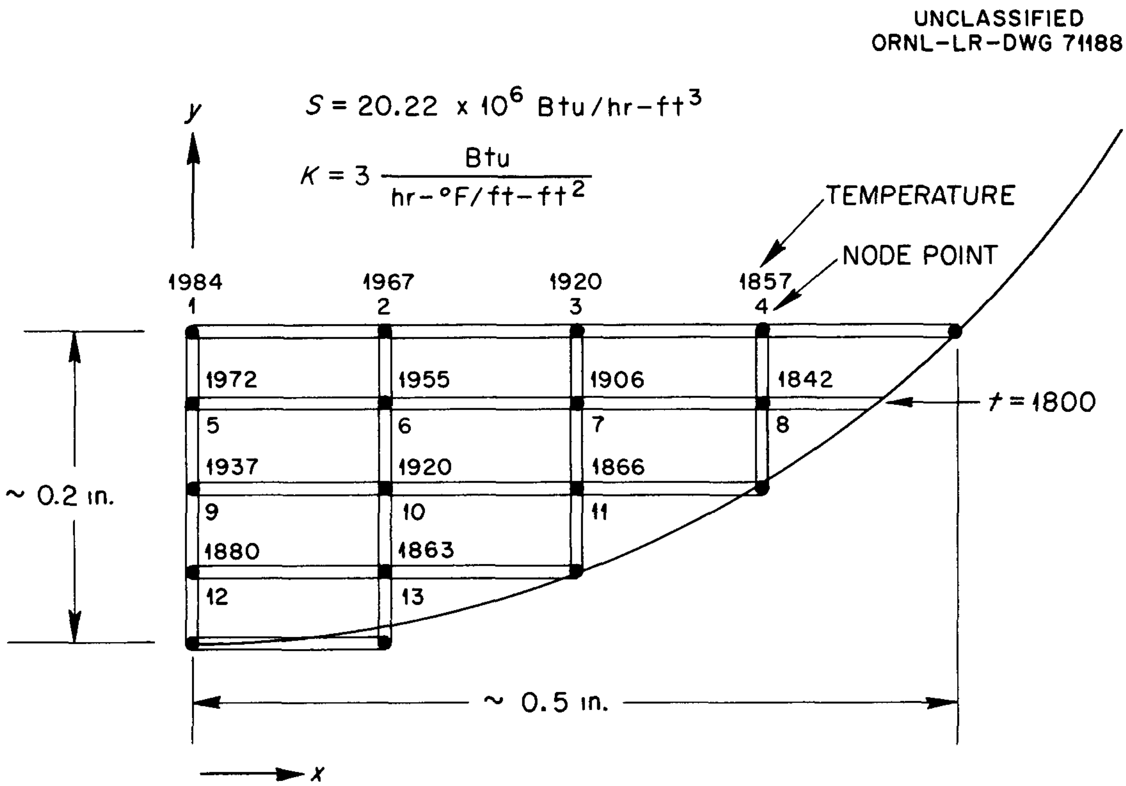

Fig. 9. Molten Salt Temperature Distribution, °F.

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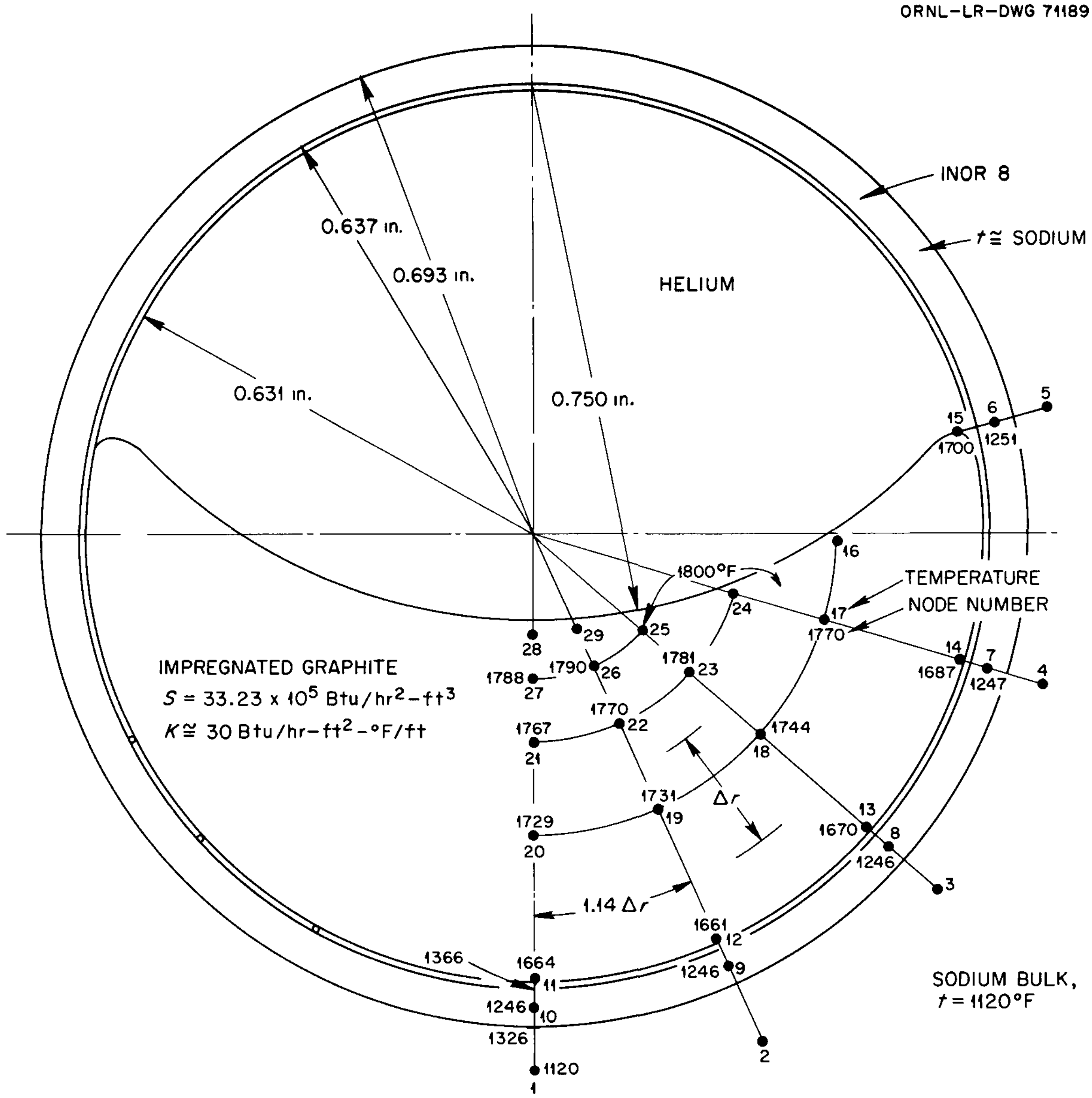

Fig. 10. Impregnated Graphite Temperature Distribution, °F.

The difference equations that must be solved simultaneously are:

$$0 = \bar{q}_{27} = 1800 + t_{21} + 1.54\ t_{26} - 3.54\ t_{27} + 5.6$$

$$0 = \bar{q}_{26} = 1800 + t_{22} + 0.77\ (1800) + 0.77\ t_{27} - 3.54\ t_{26} + 5.6$$

$$0 = \bar{q}_{21} = 1.54\ t_{22} + t_{27} + t_{20} - 3.54\ t_{21} + 11.8$$

$$0 = \bar{q}_{22} = t_{26} + t_{19} + 0.77\ t_{23} + 0.77\ t_{21} - 3.54\ t_{22} + 11.8$$

$$0 = \bar{q}_{23} = 1800 + t_{18} + 0.77\ (1800) + 0.77\ t_{22} - 3.54\ t_{23} + 11.8$$

$$0 = \bar{q}_{20} = 1.54\ t_{19} + t_{21} + t_{11} - 3.54\ t_{20} + 24.5$$

$$0 = \bar{q}_{19} = t_{22} + t_{12} + 0.77\ t_{18} + 0.77\ t_{20} + 24.5 - 3.54\ t_{19}$$

$$0 = \bar{q}_{18} = t_{23} + t_{13} + 0.77\ t_{17} + t_{19}\ (0.77) + 24.5 - 3.54\ t_{18}$$

$$0 = \bar{q}_{17} = 1800 + t_{14} + 1.54\ (1800) + 0.77\ t_{18} - 4.31\ t_{17} + 24.5$$

$$0 = \bar{q}_{11} = t_{20} + 0.77\ t_{12} + 0.118\ t_{10} - 1.888\ t_{11} + 25.5$$

$$0 = \bar{q}_{12} = t_{19} + 0.385\ t_{13} + 0.385\ t_{11} + 0.118\ t_{9} - 1.888\ t_{12} + 25.5$$

$$0 = \bar{q}_{13} = t_{18} + 0.385\ t_{14} + 0.385\ t_{12} + 0.118\ t_{8} - 1.888\ t_{13} + 25.5$$

$$0 = \bar{q}_{14} = t_{17} + 0.385\ t_{15} + 0.385\ t_{13} + 0.118\ t_{7} - 1.888\ t_{14} + 25.5$$

$$0 = \bar{q}_{15} = 1800 + 0.385\ t_{14} + 0.118\ t_{6} - 1.503\ t_{15} + 12.8$$

$$0 = \bar{q}_{10} = 0.38\ t_{9} + 0.28\ t_{11} - 0.66\ t_{10} - 0.655\ (t_{10} - t_{1})^{5/4} + 1.65$$

$$0 = \bar{q}_{9} = 0.19\ t_{10} + 0.19\ t_{8} + 0.28\ t_{12} - 0.66\ t_{9} - 0.655\ (t_{9} - 660)^{5/4} + 1.65$$

$$0 = \bar{q}_{8} = 0.19\ t_{9} + 0.19\ t_{7} + 0.28\ t_{13} - 0.66\ t_{8} - 0.655\ (t_{8} - 660)^{5/4} + 1.65$$

$$0 = \bar{q}_{7} = 0.19\ t_{8} + 0.19\ t_{6} + 0.28\ t_{14} - 0.66\ t_{7} - 0.655\ (t_{7} - 660)^{5/4} + 1.65$$

$$0 = \bar{q}_{6} = 0.19\ t_{7} + 0.28\ t_{15} - 0.47\ t_{6} - 0.655\ (t_{6} - 660)^{5/4} + 1.65$$

The applicable boundary conditions used in the solution are:

B.C. 1: $\frac{\partial t}{\partial x}(0, y) = 0$

B.C. 2: $t(x, y) = 1800°F$ (at interface with salt region)

B.C. 3: $\frac{\partial t}{\partial r} = -\frac{380}{k}(t - 1120)^{5/4}$ (natural convection)

The first boundary condition derives from the symmetry about the vertical center line. The second boundary condition matches the temperature of the fuel salt at the interface. The third boundary condition is for natural convection to the bulk sodium bath. The sodium temperature, 1120°F, was determined by trial and error.

The gas-gap and metal-wall were included in this region. Effectively, Eq. (1) was applied to each nodal volume with continuity assumed in the temperature distribution at the nodal interfaces. The results of the relaxation procedure are also shown on Fig. 10.

APPENDIX C

ORNL-MTR-47-3 Temperature Transients

The following tables summarize the temperature transients to which the ORNL-MTR-47-3 capsules were subjected as a consequence of reactor power fluctuations and adjustments to the experiment temperature and power controls. A transient is defined as a change in temperature of 30°C or more in one direction, for example, a reactor scram and recovery would cause two transients. The transient duration indicates the time required to go from the initial steady-state temperature through 90-95% of the transient to the new temperature and is a measure of the rate of temperature change. The duration of steady-state before transient is in some instances zero as in the case of a reactor scram and rapid return to power without time to reach steady-state in the scram condition. In this case, the minimum temperature reached during the scram represents the initial steady-state temperature before the increasing transient. Capsules 8, 15, and 16 are grouped together since their temperatures and responses are similar. The initial temperature is not always equal to the previous transient's final temperature since gradual temperature drifts or temperature changes of less than 30°C were not considered as transients so long as the fuel did not go through a phase (melt or freeze) change.

Table 8. ORNL-MTR-47-3 Thermal Transients[a]

MTR Cycle 156 from 5/6/61 to 5/20/61

Transient Number	Duration of Transient		Duration of Steady-State Before Transient		Steady-State Temperature, °C			
					Capsule 3		Capsule 8, 15, 16	
	Hr.	Min.	Hr.	Min.	Initial	Final	Initial	Final
1	0	40	5	15	26	185	26	162
2	0	15	0	0	186	32	162	32
3	0	24	0	45	32	330	32	290
4	0	24	0	40	372	37	321	37
5	1	0	0	45	37	537[b]	37	475[b]
6	0	24	0	40	537	934	475	815
7	0	5	11	5	934	433[c]	821	425[c]
8	0	35	0	0	433	915[b]	425	802[b]
9	0	5	14	40	921	773	815	695
10	0	8	0	30	766	245[c]	688	241[c]
11	0	7	0	0	245	760[b]	241	676[b]
12	0	10	1	15	760	921	682	808
13	0	10	21	10	921	643	815	575
14	0	10	0	0	643	915	575	802
15	0	47	43	13	941	96[c]	802	97[c]
16	0	45	17	15	49	384	49	363
17	1	10	1	35	384	568[b]	363	512[b]
18	0	10	0	35	587	921	537	821
19	0	5	24	10	921	777	826	708
20	0	10	1	45	777	915	700	821
21	0	7	62	11	915	275[c]	826	266[c]
22	0	33	0	0	275	906[b]	266	815[b]
23	1	0	1	7	926	96[c]	826	97[c]
24	0	45	14	0	49	347	49	321
25	1	10	1	35	378	572[b]	351	525[b]
26	0	10	3	0	572	860	525	764
27	0	5	14	25	865	959	770	845
28	0	13	95	17	926	173[c]	821	168[c]
29	0	25	0	0	173	926[b]	168	815[b]
30	0	25	36	0	926	96[c]	821	97[c]

[a]Changes of 30°C or more in fuel graphite interface temperatures

[b]Transient during which salt melts (melting point 445.6°C)

[c]Transient during which salt solidifies (melting point 445.6°C)

Table 9. ORNL-MTR-47-3 Thermal Transients[a]

MTR Cycle 157 from 5/24/61 to 6/11/61

Transient Number	Duration of Transient		Duration of Steady-State Before Transient		Steady-State Temperature, °C			
					Capsule 3		Capsule 8, 15, 16	
	Hr.	Min.	Hr.	Min.	Initial	Final	Initial	Final
1	0	5	62	15	43	108	43	108
2	0	50	1	15	137	445[b]	141	413
3	0	25	0	0	445	72[c]	413	73
4	0	43	0	0	72	519[b]	73	487[b]
5	0	25	3	17	537	890	487	789
6	0	23	11	12	896	120[c]	802	121[c]
7	0	30	0	0	120	537[b]	121	782[b]
8	0	37	22	33	908	120[c]	802	115[c]
9	0	40	0	0	120	908[b]	115	802[b]
10	0	40	3	18	908	85[c]	795	85[c]
11	0	30	9	10	49	360	49	345
12	0	12	0	43	36	605[b]	345	544[b]
13	1	13	0	52	587	902	538	795
14	0	9	101	58	902	221[c]	795	216[c]
15	0	9	0	0	221	476[b]	216	432
16	0	3	0	0	476	299[c]	432	290
17	0	51	0	0	299	878	290	782[b]
18	0	6	31	24	884	525	789	482
19	0	44	0	46	525	78[c]	482	79[c]
20	0	24	11	6	43	229	43	308
21	1	0	2	30	354	878[b]	321	776[b]
22	0	50	247	38	884	90[c]	789	91[c]

[a]Changes of 27.7°C or more in fuel graphite interface temperatures

[b]Transient during which salt melts (melting point 445.6°C)

[c]Transient during which salt solidifies (melting point 445.6°C)

Table 10. ORNL-MTR-47-3 Thermal Transients[a]

MTR Cycle 158 from 6/21/61 to 7/5/61

Transient Number	Duration of Transient		Duration of Steady-State Before Transient		Steady-State Temperature, °C			
					Capsule 3		Capsule 8, 15, 16	
	Hr.	Min.	Hr.	Min.	Initial	Final	Initial	Final
1	1	3	92	40	43	396	43	358
2	0	25	0	0	396	67	358	67
3	0	22	0	0	67	439	67	401
4	0	45	0	45	445	537[b]	420	488[b]
5	0	10	3	40	555	915	506	813
6	0	4	3	45	915	354[c]	813	358[c]
7	0	41	0	0	354	915[b]	358	813[b]
8	0	10	118	42	909	197[c]	815	193[c]
9	0	43	0	0	197	903[b]	193	801[b]
10	0	30	0	50	915	109[c]	808	108[c]
11	2	25	12	35	49	903[b]	50	808[b]
12	0	25	31	40	896	126[c]	808	126[c]
13	0	20	0	0	126	741[b]	126	663[b]
14	0	20	0	30	765	903	685	808
15	0	25	0	45	889	126[c]	779	126[c]
16	0	45	0	0	126	896[b]	126	779[b]
17	0	10	0	0	896	378[c]	779	358[c]
18	0	5	0	0	378	648[b]	358	594[b]
19	0	10	0	0	648	525	594	488
20	0	25	0	0	525	915	488	815
21	0	5	79	23	903	353[c]	779	339[c]
22	0	22	0	0	354	889[b]	339	782[b]
23	0	4	15	48	909	353[c]	779	402[c]
24	0	8	0	0	353	846[b]	402	738[b]
25	0	5	0	0	846	710	738	638
26	0	20	0	0	710	846	638	782
27	0	12	23	58	903	167[c]	778	163[c]
28	0	40	0	0	167	889[b]	163	777[b]
29	0	17	17	53	896	137[c]	288	139[c]
30	0	20	0	0	137	828[b]	139	719[b]
31	0	3	0	27	834	896	726	788
32	0	2	49	8	903	791	777	713
33	0	10	0	0	791	889	713	782
34	0	32	7	8	903	108[c]	777	109[c]
35	0	57	14	55	56	475[b]	56	431
36	0	8	0	0	475	312[c]	431	290
37	0	45	0	0	312	915[b]	290	815[b]
38	0	27	10	58	955	109[c]	815	109[c]

[a] Changes of 27.7°C or more in fuel graphite interface temperatures

[b] Transient during which salt melts (melting point 445.6°C)

[c] Transient during which salt solidifies (melting point 445.6°C)

Table 11. ORNL-MTR-47-3 Thermal Transients[a]

MTR Cycle 159 from 7/5/61 to 7/23/61

Transient Number	Duration of Transient		Duration of Steady-State Before Transient		Steady-State Temperature, °C			
					Capsule 3		Capsule 8, 15, 16	
	Hr.	Min.	Hr.	Min.	Initial	Final	Initial	Final
1	1	3	62	6	50	378	50	345
2	0	4	0	0	378	253	345	235
3	1	3	0	0	253	463[b]	235	475[b]
4	0	18	1	7	525	884	475	782
5	0	18	9	40	884	138[c]	782	132[b]
6	0	32	0	0	138	877[b]	132	776[c]
7	0	12	10	20	890	179[c]	788	168[b]
8	0	33	0	0	179	890[b]	168	788[c]
9	0	6	22	37	896	741	802	675
10	0	7	0	0	741	884	675	795
11	0	3	17	45	877	415[c]	795	388[b]
12	0	32	0	0	415	871[b]	388	795[c]
13	0	5	45	40	884	642	809	594
14	0	15	0	0	642	877	594	802
15	0	30	123	50	890	114[c]	795	115[b]
16	0	55	13	30	61	562[b]	61	507[c]
17	2	5	1	42	568	884	513	795
18	0	26	2	44	884	108[c]	802	108[b]
19	0	30	1	25	66	834[b]	67	763[c]
20	0	17	32	13	908	161[c]	821	157[b]
21	0	27	0	0	161	890[b]	157	795[c]
22	2	7	13	6	884	543	814	500
23	1	40	0	0	543	877	500	802
24	1	0	0	50	877	773	802	694
25	1	0	0	0	773	890	694	821
26	0	10	0	0	890	723	821	670
27	0	25	3	10	723	903	670	827
28	0	30	76	32	903	108[c]	821	109[c]

[a]Changes of 27.7°C or more in fuel graphite interface temperatures

[b]Transient during which salt melts (melting point 445.6°C)

[c]Transient during which salt solidifies (melting point 445.6°C)

Distribution

1-3. DTIE, AEC
4. M. J. Skinner