664016

DP-1013

AEC RESEARCH AND DEVELOPMENT REPORT

EFFECT OF SPACING ON HEAT TRANSFER BURNOUT IN ROD BUNDLES

R. H. TOWEI L

REG. U. S. PAT. OFF.

Savannah River Laboratory

Aiken, South Carolina

Printed in USA. Price $1.00
Available from the Clearinghouse for Federal Scientific and Technical Information, National Bureau of Standards, U. S. Department of Commerce, Springfield, Virginia

664016

DP-1013

Reactor Technology
(TID-4500)

EFFECT OF SPACING ON HEAT TRANSFER BURNOUT IN ROD BUNDLES

by

R. H. Towell

Approved by

E. C. Nelson, Research Manager
Reactor Engineering Division

November 1965

E. I. DU PONT DE NEMOURS & COMPANY
SAVANNAH RIVER LABORATORY
AIKEN, SOUTH CAROLINA

CONTRACT AT(07-2)-1 WITH THE UNITED STATES ATOMIC ENERGY COMMISSION

ABSTRACT

The burnout heat flux for boiling light water in a mockup of the central cooling channel of a multi-rod fuel bundle did not change appreciably when the space between the rods was decreased to as little as 0.018 inch. Burnout heat fluxes measured with forced boiling flow were

- twice the values reported for some multirod test sections with comparable rod spacings (0.015 to 0.050 inch)

- about 50% higher than values reported for larger rod spacings (>0.070 inch).

The higher heat fluxes are attributed to the relatively uniform cooling that was obtained in the mockup by use of a single coolant channel of a symmetrical shape. Such high heat fluxes probably cannot be duplicated in rod bundles that have nonuniform coolant channels.

CONTENTS

LIST OF TABLES AND FIGURES

EFFECT OF SPACING ON HEAT TRANSFER BURNOUT IN ROD BUNDLES

INTRODUCTION

Studies by Atomic Energy of Canada Limited[1] indicate that D_2O-moderated reactors cooled by boiling H_2O have considerable promise for producing low cost power. The cooperative program between the United States and Canadian governments for D_2O-moderated reactors has sponsored research for developing heat transfer data for this reactor type (boiling-light-water-cooled) in which the assembly tested was a mockup of a full-scale 19-rod fuel bundle. The Technical Advisory Committee for the cooperative program believed that the heat transfer studies would be strengthened if a fundamental study were conducted on boiling heat transfer in which the test section was a mockup of a single coolant channel that surrounds a central rod of a 19-rod bundle. The Savannah River Laboratory was asked to undertake such a study.

The amount of H_2O in the coolant channels of a fuel assembly should be minimized for a practicable design for a D_2O-moderated reactor because of the large parasitic absorption of neutrons by H_2O. The coolant volume can be reduced by closely spacing the fuel rods in the bundle, provided of course, that the burnout heat flux is not seriously affected. The burnout heat flux for multirod assemblies of various spacings has been studied in other laboratories. However, the effect of rod spacing has been obscured by other factors, particularly by imperfect distribution of coolant flow and by the spacers that separate the rods from one another in the bundle. The separate effect of rod spacing on boiling burnout is the subject of this report.

SUMMARY

The burnout heat flux for boiling light water in a mockup of the central cooling channel of a multirod fuel bundle did not change appreciably when the space between the rods was decreased to as little as 0.018 inch. The observed heat fluxes are more than twice as high as some of the values reported in the literature for multirod test sections that contain several interconnected coolant channels. The higher heat fluxes are attributed to the relatively uniform cooling that was obtained by use of a single coolant channel of symmetrical shape. Such high heat fluxes probably cannot be duplicated in rod bundles that have nonuniform coolant channels. Further heat transfer work on fuel mockups with closely spaced rods will be required to assess the magnitude of such detrimental effects as rod spacers, an unheated housing tube wall, and interconnected coolant passages of various shapes.

The burnout heat flux ranged from 320,000 pcu/(hr)(ft^2) at 46% steam quality to 630,000 pcu/(hr)(ft^2) at 24% quality. The tests were conducted at a pressure of 1000 psia, with mass velocities ranging from about 1-2 million lb/(hr)(ft^2), and with uniform axial heating.

DISCUSSION

BACKGROUND

The minimum flow area in a rod bundle (the AECL reference assembly) is obtained when all the components contact each other. However, the power level of this assembly would be reduced by overheating and premature burnout in the contact regions. Earlier tests at SRL[2] showed that the burnout heat flux is decreased locally when a fuel element is contacted by a spacer rib that prevents local heat transfer to the coolant. These tests also showed that the local effect was virtually eliminated when the gap between the spacer rib and heated surface was ~0.020 inch. Although these tests were made with subcooled boiling, the results indicated that the burnout heat flux would not be seriously reduced in an assembly with rods spaced much closer than the usual design of ≥0.070 inch.

LITERATURE REVIEW

No unequivocal measurements of heat transfer burnout in compact rod bundles were found in the literature. Levy, et al.[3] measured the burnout heat flux of an eccentric annulus and found no effect of eccentricity until the gap was reduced to 0.030 inch. Further displacement of the heater from the center of the annulus probably caused large local variations in the coolant enthalpy which reduced the burnout heat flux.

Lee and Little[4] measured the burnout heat flux of a dumbbell-shaped channel formed by squeezing a round tube across a diameter. They found that the burnout heat flux remained constant as the gap was reduced from 0.217 to 0.045 inch. The burnout site was in a lobe section until the heat flux in the gap section was increased ~40%. Becker[5] explained the preferential burnout in the lobe by pointing out that in two-phase annular flow, burnout would be expected to occur where the annular film is subjected to the largest shear stress.

The dumbbell section approximates a portion of a rod bundle more closely than an eccentric annulus does, but the local quality and shear stress may still have been much different than in a rod bundle.

Burnout measurements have been reported in the literature for multirod test sections with several rod spacings. The coolant channels in such sections are divided into 2 to 5 types of subchannels depending on: local cross-sectional area between components; heat transfer surface area; total surface area; and heat flux (if the rods are operated at different powers). The enthalpy of the effluent from each type of subchannel is usually different, but in burnout tests of multirod assemblies the mixed-mean enthalpy of the assembly effluent is the reported value. The local enthalpy, rather than the mixed-mean enthalpy, probably determined burnout of an individual rod. Local enthalpy was not measured due to experimental difficulty. Therefore, only those results obtained in multirod test sections with similar subchannel enthalpies are expected to be comparable. Knudsen[6] points out the exception: "It was found that good agreement existed for those multirod configurations which had large rod spacings [$\geqslant$0.074 inch] so that interchannel mixing was not restricted and/or in which the heat flux distribution was adjusted so that there was small variation in local enthalpy even under poor mixing conditions".

Waters, et al.[7] measured the burnout heat flux in 19-rod bundles with 0.074, 0.050, and 0.015-inch rod spacing. Rod spacing was maintained by helical wire wraps that also promoted interchannel mixing.[8] At a mass velocity of 10^6 lb/(hr)(ft^2) and a mixed-mean effluent quality of 5%, the burnout heat flux of the 0.015-inch spacing was about one-third that of the 0.074-inch spacing. The burnout heat flux of the 0.050-inch spacing was about 1/2 that with 0.074-inch spacing. With both the 0.050- and 0.015-inch spacing larger percentages of their flow areas were between the housing tube and the outer rods than with the 0.074-inch spacing, which probably resulted in increasingly large differences in subchannel enthalpies. Knudsen[6] attributed the decrease in burnout heat flux with decreasing rod spacing to subchannel enthalpy imbalances.

Matzner, et al.[9-11] demonstrated that the burnout heat flux of individual rods can be increased by balancing subchannel enthalpies in a multirod assembly. The SNAP-4A test section (Figure 1) was composed of 12 rods on an equilateral triangular pitch with 0.022-inch spacing between rods and a contoured housing that provided a 0.022-inch uniform gap around the outer rods. Spacing was maintained by wire wraps on all rods. The rod in the obtuse corner burned out preferentially probably because the local quality in the channel between the rod and the housing was much greater than in the other channels.[6-12]

In a second test by Matzner[10], subchannel enthalpies were more nearly balanced by increasing the power of the two interior rods 55% above the power of the exterior rods. Burnout occurred on an interior rod at a heat flux 50% above that of the uniformly heated test section.

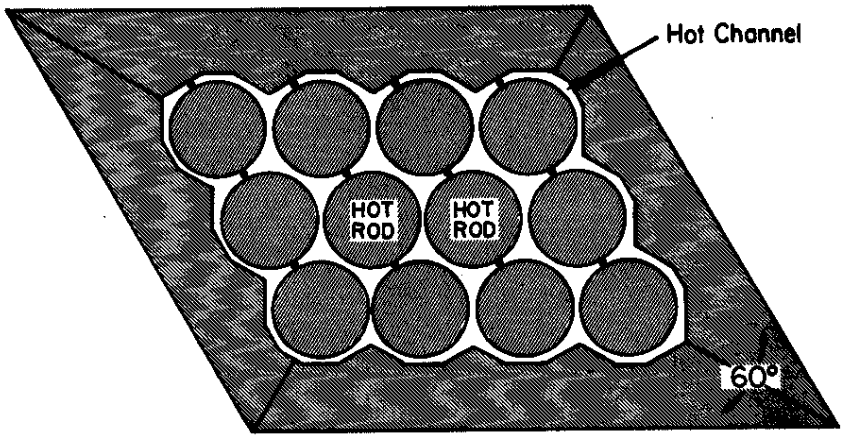


FIG. 1 SECTION OF SNAP-4A FUEL ELEMENT (WITH 0.022-INCH SPACING)

The increase in burnout heat flux was probably caused by redistribution of the coolant that reduced the local quality in the exterior channels. In an attempt to balance subchannel enthalpies with uniform rod power, the spacing was increased to 0.032 inch between the exterior rods and the housing, and 0.042 inch between the rods in the obtuse corner and the housing.[11] Burnout occurred on the exterior rods at heat fluxes 5 to 25% higher than in the original SNAP-4A test section. The increased burnout heat flux was also probably due to reduced local quality in the exterior channels of the assembly.

Another factor that apparently depresses burnout conditions in multirod assemblies is the "unheated wall effect". This effect, which was first described by Becker[5], occurs in the annular flow regime where the liquid coolant is distributed in a film on the walls and in droplets in the continuous vapor phase. Because no evaporation occurs on unheated surfaces, a disproportionate amount of liquid collects on them and is not available to cool the fuel rods. Thus unheated surfaces in a fuel assembly result in poor utilization of the coolant, and causes the mixed-mean quality in the subchannel to be less than the effective local quality. The "unheated wall effect" is closely related to subchannel enthalpy imbalances discussed above, because both effects may disturb the relationship between the local quality at the burnout site and the mixed-mean quality.

DESCRIPTION OF TEST SECTION

The SRL test section was a 4-foot-long mockup of the central rod and six intermediate rods of a 19-rod bundle (Figure 2). Rods were spaced on an equilateral triangular pitch similar to the central region in a 19-rod bundle. This arrangement (Figure 3) enabled tests

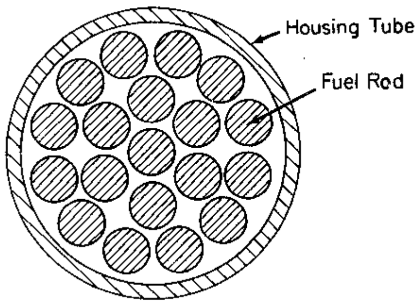


FIG. 2 TYPICAL 19-ROD BUNDLE

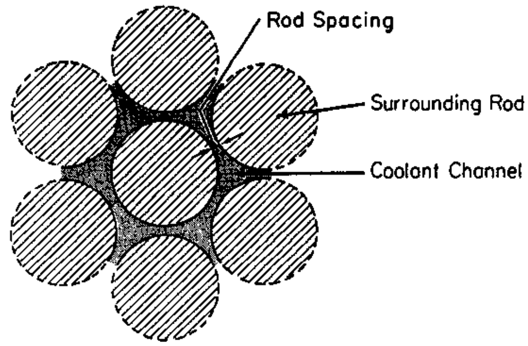


FIG. 3 SECTION OF ROD BUNDLE MOCKED UP BY SRL TEST SECTION

where a) the mixed-mean effluent quality was more closely related to the local quality about a single rod than in a multirod test section, and b) rod spacing could be varied without altering the enthalpy relationship.

MOCKUP OF THE INTERMEDIATE RODS (surrounding-rod mockup)

The six intermediate rods were joined together to form a star-shaped, annular coolant channel about the central rod (Figure 4). A copper bar was split lengthwise, the contour of the star-shaped channel was milled into the flat face of each half, and the halves were rejoined by brazing. A protective coating of nickel was chemically plated on the surface of the channel. The channel was 54 inches long and had tapered entrances.

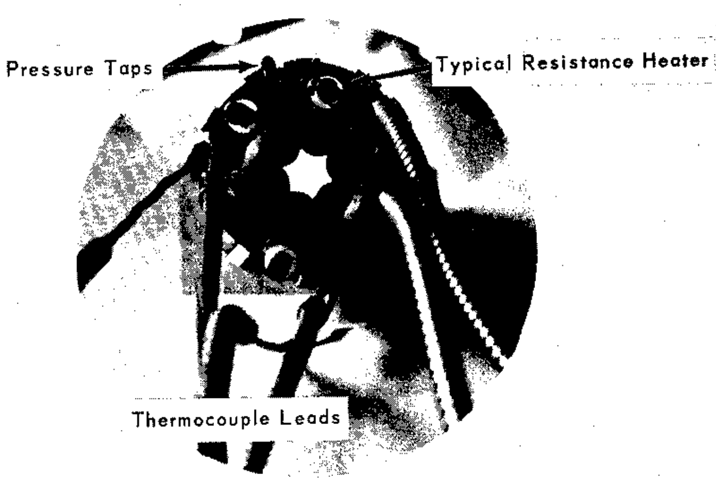


FIG. 4 END VIEW OF SURROUNDING-ROD MOCKUP

Six resistance heaters, operated from a 440-volt AC source, dissipated up to 300 kw at the periphery of the mockup. The heated length was 48 inches. Slots were milled in the outside of the copper bar to receive the heaters, and appropriately shaped backup pieces were placed behind them. Thermocouples and pressure taps monitored temperatures and pressure drops.

The mockup was sealed inside an insulated, stainless steel pressure vessel fitted to connect the star-shaped channel to the flow loop (Figure 5). The sheaths of two heaters cracked when seal welded. Welding weakened the sheaths of the remaining heaters, which also failed after several tests.

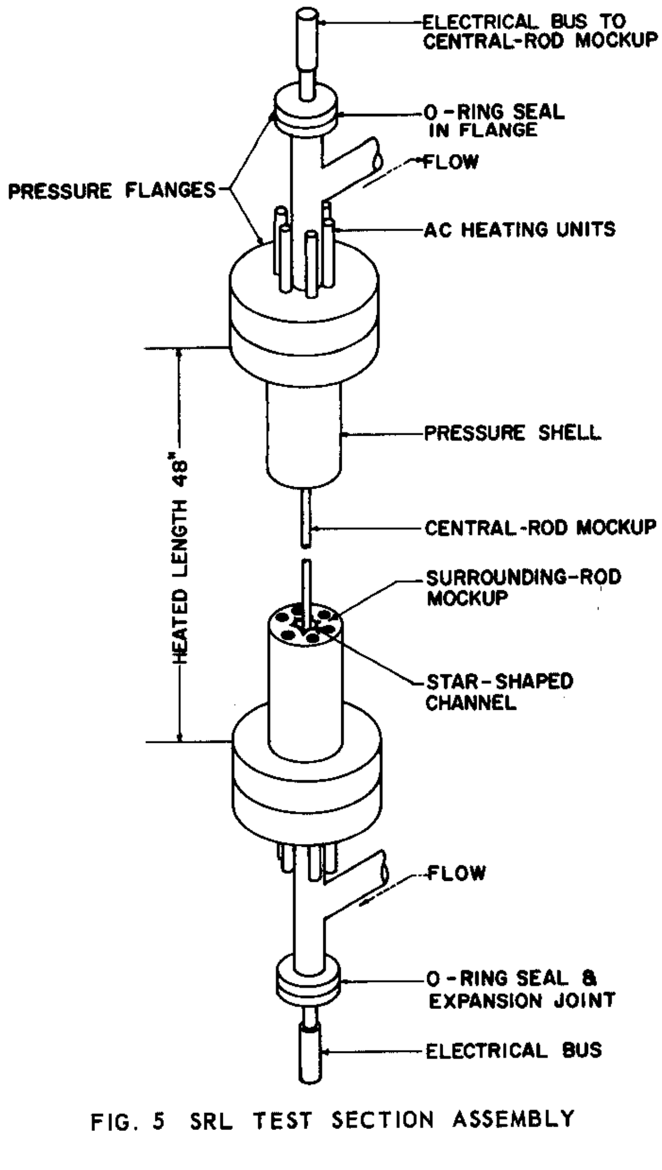


FIG. 5 SRL TEST SECTION ASSEMBLY

CENTRAL-ROD MOCKUP

The central rod was mocked up by 48-inch-long stainless steel tubes that were resistance heated by low-voltage DC. The wall thickness of the tubes used in the tests varied up to ±5% and produced a corresponding variation in the local heat flux in any transverse section. Two sizes of tubes (0.500- and 0.564-inch) were used as the central rod to change the rod spacing from 0.050 to 0.018 inch (Figure 3).

Power for the central-rod mockup was supplied by eight welding generators (rated at 40 volts and 300 kw) operating in parallel.[13] Current was conducted to the heated section by stainless-steel-clad copper buses of the same outside diameter as the heated section. The ends of the buses passed through O-ring seals in the high pressure vessel; thermal expansion was taken up by motion through one seal. Coolant was supplied to the bottom of the test section through stainless steel pipes and fittings.

The central rod was not electrically insulated, and any contact between it and the surrounding-rod mockup resulted in an electric arc that destroyed the central rod and damaged the surface of the star-shaped channel. The central rod bowed from differential thermal expansion whenever the coolant temperature about its circumference was not uniform. Bowing was restricted by short spacer ribs placed at about 3 inch intervals throughout the heated length (Figure 6). These ribs were fabricated from a phenolic, quartz-fiber laminate that withstood the 275°C wet mixture and the necessary handling. The ribs (0.050 inch wide, 0.280 inch long) were aligned with the coolant flow with the corners rounded for streamlining. By the use of these ribs, the spacing between the mockups was maintained within ±0.006 inch.

The ribs were staked into slots milled into the surface of the central rod; the two mockups were indexed to orient the ribs on lines passing through the centers of the six surrounding rods and the central rod. The average heat flux at the ribs was about 7% higher than the nominal value due to increased electrical resistance at the rib slots. In the initial tests, the spacers were 0.040-inch-diameter sapphire pins that disturbed the coolant flow and heat flux less than the spacer ribs; however, they broke during operation and were replaced after two tests.

The central-rod mockup was instrumented to detect burnout and to monitor the wall temperature. Voltage taps were spot welded to the inside wall of the heated tube at 2, 4, 6, and 8 inches from the effluent end; the lead wires passed through coaxial holes in the electrical buses. Local resistances of the heated tube between voltage taps were compared with bridge circuits. Burnout, i.e., imminent local melting, was detected by an imbalance of the bridge circuits.

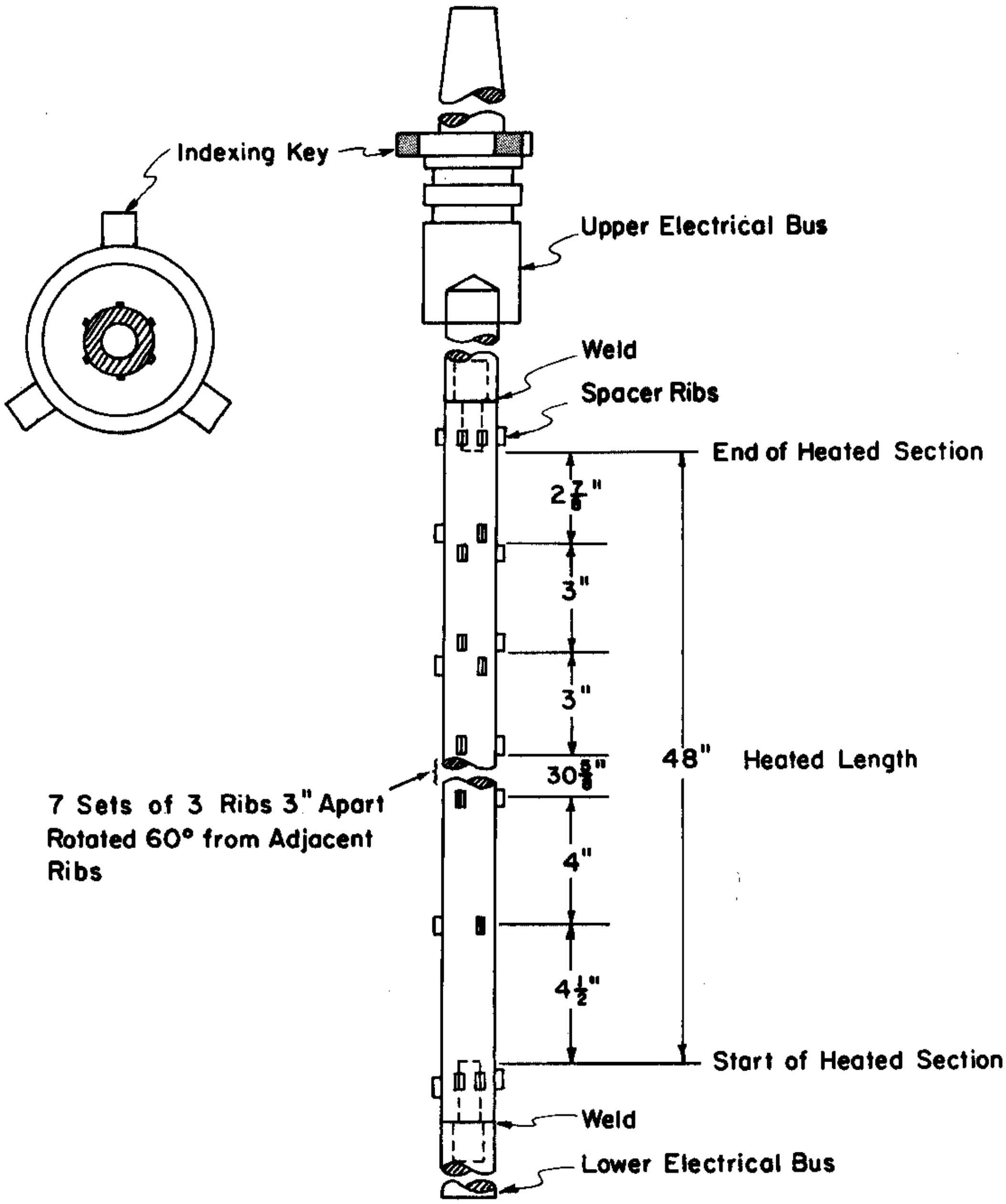


FIG. 6 CENTRAL-ROD MOCKUP AND SPACER RIBS

SUPPORTING EQUIPMENT

The flow loop is shown in Figure 7. Inlet flow was measured by a turbine flowmeter. Effluent from the test section was condensed by a bypass stream of subcooled water, and the combined flow was recirculated through the pump and heat exchanger. Nitrogen was used to pressurize the flow loop via a tank through which there was no circulation. Expansion of the coolant was accommodated by discharging nitrogen from the pressurization tank. Entrained gases in the coolant were separated by low velocity flow through a 6-inch pipe.

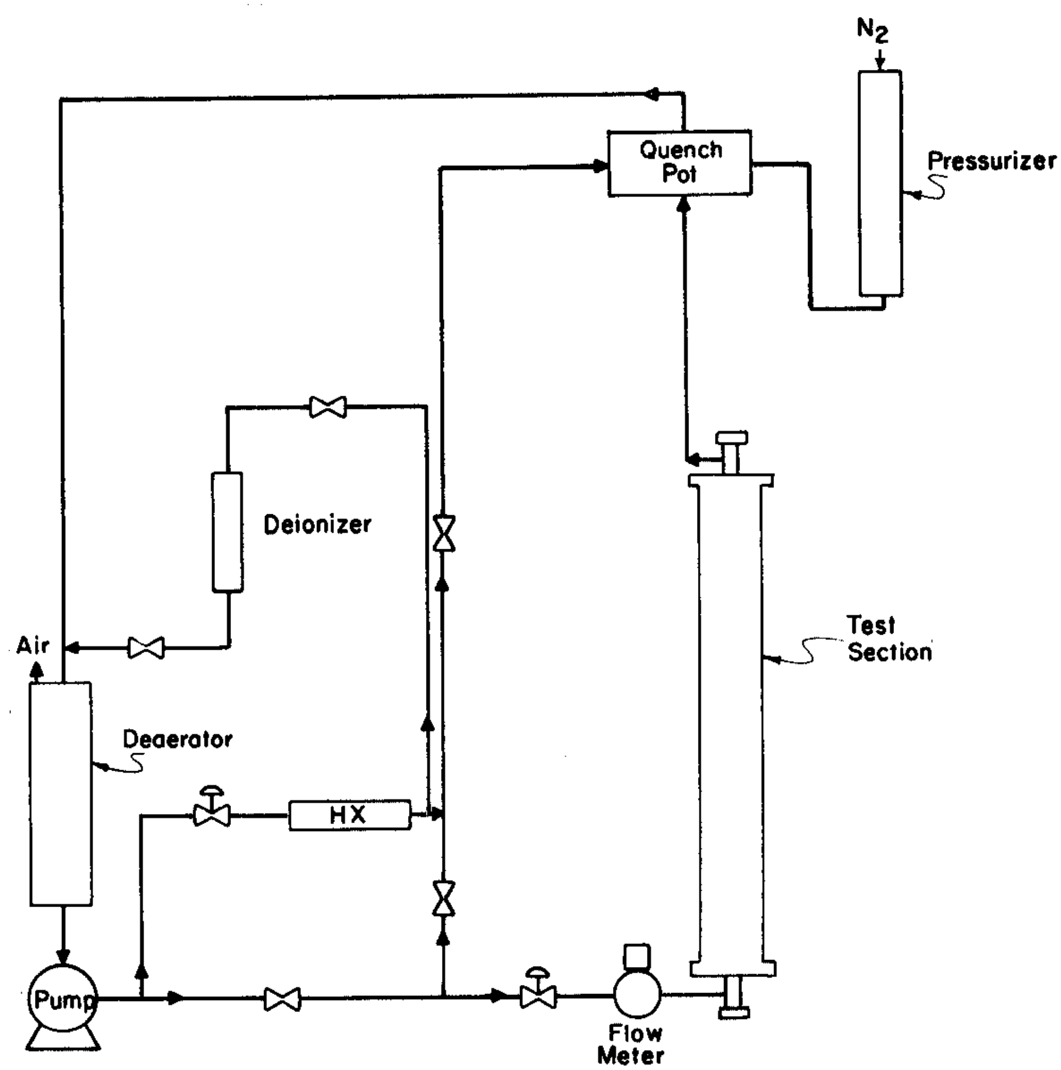


FIG. 7 SCHEMATIC OF HIGH PRESSURE FLOW LOOP

RESULTS

The results of 11 burnout tests are presented in Table I. The qualities given are calculated values for the effluent. In tests that ended by melting of the central-rod mockup, the rod always failed about 1 inch from the effluent end of the heater. Test NB values were obtained just prior to shutdown of a test that could not be continued to burnout. In all the tests the central rod was operated at a heat flux higher than that of the surrounding rods to avoid damaging the mockup. Heat balances were calculated after each power or flow adjustment and before the effluent reached the saturation temperature; they generally agreed within ±5%.

TABLE I

Test Results

Test No.[a]	Burnout Heat Flux Central Rod, pcu/(hr)(ft^2)	Mass Flow Rate, 10^6 lb/(hr)(ft^2)	Effluent Quality, %	Heat Flux Surrounding Rods,[c] pcu/(hr)(ft^2)	Influent Subcooling, °C
		Spacing - 0.050 inch			
1	390,000	1.0	29	0	58
2	510,000	1.0	21	0	133
3	490,000	1.1	27	0	87
4	370,000	1.0	40	120,000	112
5	320,000	1.0	46	120,000	76
6	480,000	1.9	19	120,000	84
7	570,000	2.0	16	120,000	101
8	620,000	2.3	19	120,000	83
9	630,000	1.9	24	0	54
NB[b]	390,000	1.7	35	190,000	56
		Spacing - 0.018 inch			
10	410,000	1.2	34	0	113
11	490,000	1.4	32	0	129

(a) All tests were made at a pressure of ~1000 psia.
(b) Maximum conditions, did not reach burnout.
(c) Only two of the six surrounding resistance heaters operating 180° apart.

EFFECT OF ROD SPACING

Results of two tests indicate that heat transfer burnout in a rod bundle is not affected by component spacings as small as 0.018 inch. Heat fluxes and qualities measured at burnout (Tests 10 and 11) with 0.018-inch rod spacing were slightly above the values measured in similar tests (Tests 1 and 3) with 0.050-inch spacing.

Burnout heat fluxes measured in the SRL test section were more than twice values reported for some multirod test sections with comparable spacings. In Figure 8, the SRL results at a mass velocity of $\sim 10^6$ lb/(hr)(ft^2) are compared with results obtained by Waters, et al.[7] on rod bundles with 0.015- and 0.050-inch spacings. The differences are probably due to enthalpy imbalances that occurred in the subchannels of the multi-rod test sections. As discussed previously, burnout of an individual rod in an array is probably related to the local coolant conditions and not to the mixed-mean coolant condition, which is the abscissa in Figure 8. Because the coolant channel in the SRL test section was symmetrical about the central rod for both rod clearances, the mixed-mean quality is more closely related to the local conditions that affect burnout.

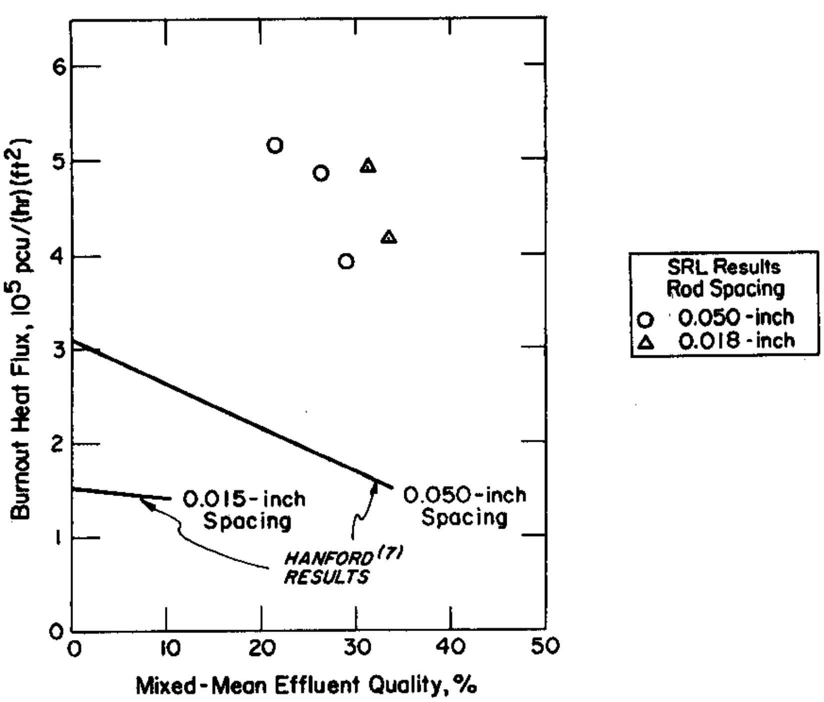


FIG. 8 EFFECT OF ROD SPACING ON BURNOUT COMPARISON WITH HANFORD MULTIROD RESULTS

Mass Velocity $\sim 10^6$ lb/(hr)(ft^2)

SRL results are also 50% above the results obtained in multirod test sections[6] that had more uniform subchannel enthalpies because of large rod spacings (⩾0.074-inch) which promoted interchannel mixing. In Figures 9 and 10, SRL results are compared to results with large rod spacings.[7,14,15,16,17] The lower burnout heat fluxes with these multirod test sections is probably due, in part, to subchannel enthalpy imbalances.

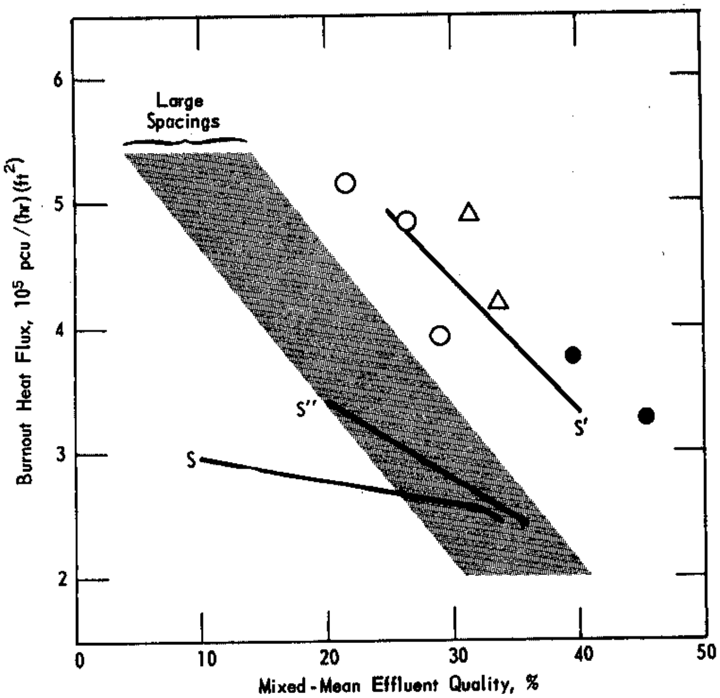
The SRL results agree well with the burnout heat fluxes of the hot rods (the 2 interior rods operating at 55% higher heat flux than the exterior rods) in the SNAP-4A tests. As discussed previously, adjustments to both the individual rod flux and subchannel flow area in the SNAP-4A tests increased the burnout heat flux through favorable redistributions of the coolant that reduced the enthalpy imbalance.

The lower burnout heat fluxes of some multirod test sections may be partially due to the helical wire wraps used to maintain rod spacing. Matzner and Neill[14] reported that burnout was always associated with the wire wraps. As the two-phase coolant flows over such wires, the boundary layer may separate from the surface, prematurely rupture the liquid film just downstream of the wire and reduce the burnout heat flux. Burnout did not occur near the spacer ribs in the SRL tests indicating that the spacers did not interfere with the liquid film flow as did the wire wraps.

EFFECT OF HEAT GENERATION IN SURROUNDING RODS

At a mass velocity of $\sim 10^6$ lb/(hr)(ft^2), the effluent quality at burnout was increased by heating the surrounding rods (Tests 1 through 5). However, at $\sim 2\times10^6$ lb/(hr)(ft^2) and ~20% effluent quality, lower burnout heat fluxes were observed when the surrounding rods were heated (Tests 6 through 9). A possible explanation of this behavior is that the annular flow regime is not fully developed at qualities ⩽20% and at mass velocities of $\sim 2\times10^6$ lb/(hr)(ft^2). This explanation is supported by Test NB. In this test, heat generation in the surrounding rods was increased over that in Test 6 and the central-rod heat flux was decreased 20% so that higher effluent qualities could be reached before burnout. The effluent quality in Test NB reached 35% when the test was shut down short of burnout because of loop operation problems. This quality is higher than would be predicted from the test results shown in Figure 10 and indicates that heat generation in the surrounding rods may produce a significant increase in the mixed-mean effluent quality under some conditions.

Only two (180° apart) of the six resistance heaters in the surrounding-rod mockup were operable in the above tests. The burnout heat flux measured in these tests may be low, because the nonuniform heat flux from the surrounding rods could result in poor utilization of the coolant.



SRL TEST RESULTS

Symbol	Rod Spacing	Surrounding-Rod Heat Flux
○	0.050 inch	zero
●	0.050 inch	120,000 pcu/(hr)(ft^2)
Δ	0.018 inch	zero

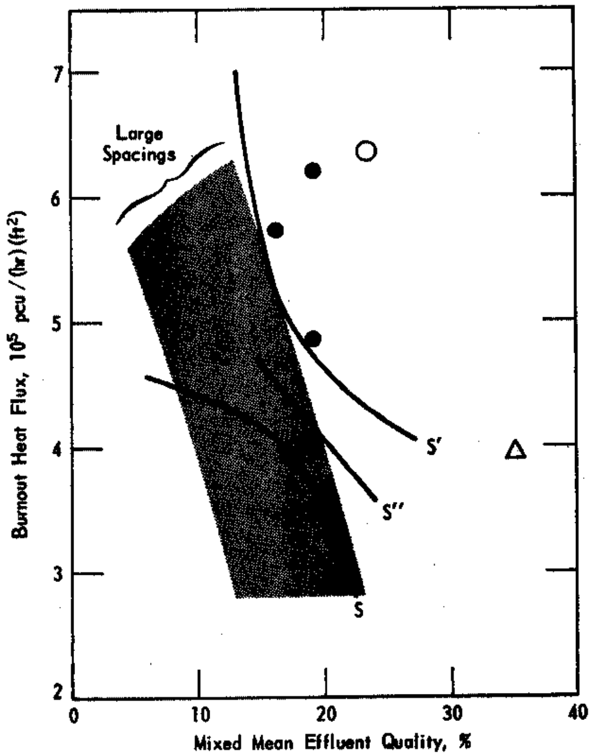
RESULTS AT OTHER SITES

Symbol	Rod Spacing	No. of Rods	Spacing Device	Site	Reference
Large Spacings	0.074 inch	19	Wire Wrap	Hanford	Waters, et al.[7]
	0.083 inch	7 and 19	Wire Wrap	Columbia U.	Matzner and Neill[14]
	0.187 inch	4	Pins	San Jose	Hench[15]
	0.170 inch	9	Ferrules	San Jose	Polomik and Quinn[17]
	0.100 inch	7	Ferrules	UKAEA	Macbeth[16]
	0.085 inch	19	Wire Wrap	UKAEA	Macbeth[16]
S	0.022 inch	12	Wire Wrap	Columbia U. (SNAP-4A)	Matzner[9]
S'(a)	0.022 inch	12	Wire Wrap	Columbia U. (SNAP-4A)	Matzner[10]
S''(b)	0.022 inch	12	Wire Wrap	Columbia U. (SNAP-4A)	Matzner[11]

(a) Power of internal rods 55% higher than power of external rods

(b) External channel enlarged to 0.032 inch

FIG. 9 COMPARISON WITH MULTIROD RESULTS
Mass Velocity ~1 x 10^6 lb/(hr)(ft^2)



SRL TEST RESULTS

Symbol	Rod Spacing	Surrounding Rod Heat Flux
○	0.050 inch	zero
●	0.050 inch	120,000 pcu/(hr)(ft²)
Δ	0.050 inch	190,000 pcu/(hr)(ft²) No Burnout

RESULTS AT OTHER SITES

Symbol	Rod Spacing	No. of Rods	Spacing Device	Site	Reference
Large Spacings	0.074 inch	19	Wire Wrap	Hanford	Waters, et al.[7]
	0.083 inch	7 and 19	Wire Wrap	Columbia U.	Matzner and Neill[14]
	0.187 inch	4	Pins	San Jose	Hench[15]
	0.170 inch	9	Ferrules	San Jose	Polomik and Quinn[17]
	0.100 inch	7	Ferrules	UKAEA	Macbeth[16]
	0.085 inch	19	Wire Wrap	UKAEA	Macbeth[16]
S	0.022 inch	12	Wire Wrap	Columbia U. (SNAP-4A)	Matzner[9]
S'[a]	0.022 inch	12	Wire Wrap	Columbia U. (SNAP-4A)	Matzner[10]
S''[b]	0.022 inch	12	Wire Wrap	Columbia U. (SNAP-4A)	Matzner[11]

[a] Power of internal rods 55% higher than power of external rods

[b] External channel enlarged to 0.032 inch

FIG. 10 COMPARISON WITH MULTIROD TESTS
Mass Velocity ~ 2 x 10^6 lb/(hr)(ft²)

EFFECT OF MASS VELOCITY

The test results indicate an increase in burnout heat flux at ~20% effluent quality when the mass velocity was increased from $1x10^6$ to $2x10^6$ lb/(hr)(ft^2) (Tests 2 and 9). With the surrounding rods heated, the burnout heat flux increased ~30% as the mass velocity increased from 1.9 to $2.3x10^6$ lb/(hr)(ft^2) (Tests 6 and 8). Most of the references indicate that the burnout heat flux decreases with increasing mass velocity. However, recent experiments[12,18] indicate that the burnout heat flux is independent of mass velocity. Further tests over wider ranges of conditions would be required to determine the effect of mass velocity on burnout of compact bundles.

HYDRAULIC PERFORMANCE

The test section was operated with inlet orificing 3 to 5 times the ΔP across the test section so that the system was hydraulically stable. Pressure drops measured across the last 32 inches and last 8-1/2 inches (common outlet tap) of the heated length are shown in

FIG. 11 EFFECT OF ROD SPACING ON PRESSURE DROP. Mass Velocity 10^6 lb/(hr)(ft^2).

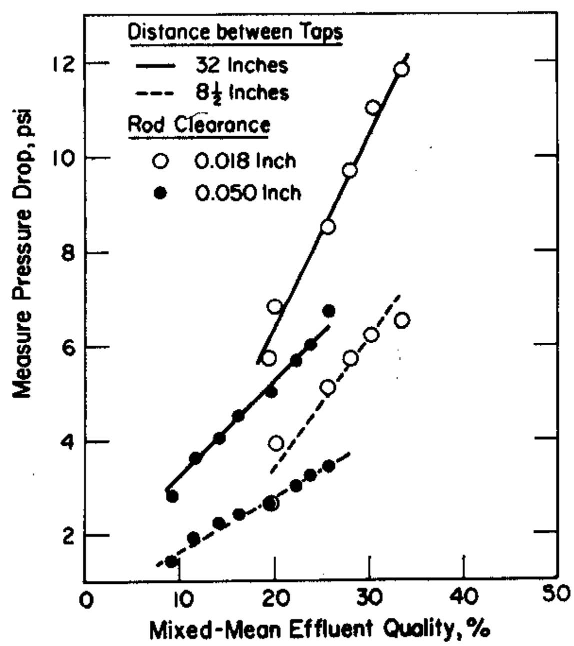


Figure 11. As expected, the larger accumulated volume of steam at the outlet of the test section caused the pressure gradient at the effluent end to be larger than the pressure gradient of the entire section. The ΔP (at the same mass velocity) with 0.018-inch spacing is higher than with 0.050-inch spacing, due to the reduction in equivalent diameter. The measured ΔP's agree within 5% with that predicted by the homogenous model[19,20] when corrected for the hydraulic resistance of the spacer rib.

BIBLIOGRAPHY

1. Committee of AECL Staff. Power Reactor Development Evaluation. Atomic Energy of Canada Report AECL-1730, Atomic Energy of Canada Limited, Chalk River, Ontario (1963).

2. S. Mirshak and R. H. Towell. Heat Transfer Burnout of a Surface Contacted by a Spacer Rib. USAEC Report DP-562, E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, S. C. (1961).

3. S. Levy, E. E. Polomik, C. L. Swan, A. W. McKinney. "Eccentric Rod Burnout at 1000 lbf/in^2 with Net Steam Generation." Int. J. of Heat and Mass Transfer 5, 595 (1962).

4. D. H. Lee and R. B. Little. Experimental Studies of the Effect of Rod Spacing on Burnout in a Simulated Rod Bundle. United Kingdom Atomic Energy Authority Report AEEW-R-178, Atomic Energy Establishment, Winfrith, Dorset, England (1963).

5. K. M. Becker. "Burnout Conditions for Flow of Boiling Water in Vertical Rod Clusters." A.I.Ch.E. Journal 9, No. 2, 216 (1963).

6. J. G. Knudsen. The Effect of Mixing on Burnout in Multirod Bundles. USAEC Report HW-84525, General Electric Co., Hanford Atomic Products Operation, Richland, Washington (1964).

7. E. D. Waters, G. M. Hesson, D. E. Fitzsimmons, and J. M. Batch. Boiling Burnout Experiments with 19-Rod Bundles in Axial Flow. USAEC Report HW-77303, General Electric Co., Hanford Atomic Products Operation, Richland, Washington (1963).

8. E. D. Waters. Fluid Mixing Experiments with a Wire-Wrapped 7-Rod Bundle Fuel Assembly. USAEC Report HW-70178(Rev.), General Electric Co., Hanford Atomic Products Operation, Richland, Washington (1963).

9. B. Matzner. Heat Transfer and Hydraulic Studies for SNAP-4 Fuel Element Geometries. Topical Report #2. USAEC Report TID-19563, Columbia University Engineering Research Center, New York, New York (1963).

10. B. Matzner. Heat Transfer and Hydraulic Studies for SNAP-4 Fuel Element Geometries. Topical Report #3. USAEC Report TID-20046, Columbia University Engineering Research Center, New York, New York (1964).

11. R. Biderman and B. Matzner. Heat Transfer and Hydraulic Studies for SNAP-4 Fuel Element Geometries. Topical Report #4. USAEC Report TID-22014, Columbia University Engineering Research Center, New York, New York (1964).

12. L. Bernath, P. D. Cohn, and T. J. Sadowski. "Forced Convection Burnout for Water in Rod Bundles at High Pressures." Int. J. of Heat and Mass Transfer 7, No. 12, 1385 (1964).

13. B. H. Butler. Parallel Operation of Welding Generators. USAEC Report DP-482, E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, S. C. (1960).

14. B. Matzner and J. S. Neill. Forced-Flow Boiling in Rod Bundles at High Pressure. USAEC Report DP-857, E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, S. C. (1963).

15. J. E. Hench. Multi-Rod (Four-Rod) Critical Heat Flux at 1000 psia. USAEC Report GEAP-4358, General Electric Co., Atomic Power Equipment Department, San Jose, California (1963).

16. R. V. Macbeth. Burnout Analysis. Part 5. Examination of Published World Data for Rod Bundles. United Kingdom Atomic Energy Authority Report AEEW-R-358, Atomic Energy Establishment, Winfrith, Dorset, England (1964).

17. E. E. Polomik and E. P. Quinn. Multi-Rod Burnout at High Pressure. USAEC Report GEAP-3940, General Electric Co., Atomic Power Equipment Department, San Jose, California (1962).

18. J. M. Batch, G. M. Hesson, and D. E. Fitzsimmons. Fog Cooled Tests. USAEC Report BNWC-27-7, Battelle-Northwest, Richland, Washington (1965).

19. J. C. Jensen. IBM 650 Routine VII Pressure Drop in Channels with Boiling. USAEC Report DP-597, E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, S. C. (1961).

20. N. Dinos. Pressure Drop for Flow of Boiling Water at High Pressure. USAEC Report DP-698, E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, S. C. (1962).

REPORT DATA SHEET

TECHNICAL DIVISION
SAVANNAH RIVER LABORATORY

HSA 10/5/65

Report Number DP-1013 S C (U) Approved by R. H. Towell

Author(s)

Title Effect of Spacing on Heat Transfer Burnout in Rod Bundles

Division RED

Indicate known prior art As in Bibliography

Approval (Introduction, Summary, Cover Letter) jwm 8/27/65 Section Director; [signature] 9/24 Laboratory Director

	Author	Supv.	Div. Hd.
Manuscript Approval (MS)	R. H. Towell 8/25/65	[signature] 8/25/65	E [signature] 9/13/65
Reproduction Copy Approval (RC)	R. H. Towell 12/2/65	....	E [signature] 12/3/65
Recommended for Publication		....	

Publication in

Presentation at

TO BE COMPLETED BY TIS

UC-80

Category Reactor Technology TID-4500 41st Ed

Classification of Abstract U HSA 10/5/65

Classification of Title U

Transmittal Letter DP 1013 TL S C (U)

No. of copies for Distribution

Internal
TID-4500
M-3679
Special
AECL
TOTAL

Approved by

Total Pages

Price

800

OSR-24-A40(Rev. 2/61)