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AEC RESEARCH AND DEVELOPMENT REPORT

HEAVY WATER MODERATED POWER REACTORS

PROGRESS REPORT
JANUARY-FEBRUARY 1965

Technical Division
Wilmington, Delaware

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HEAVY WATER MODERATED POWER REACTORS
PROGRESS REPORT
January - February 1965

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Wilmington, Delaware

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ABSTRACT

The Heavy Water Components Test Reactor (HWCTR) was placed in standby condition upon termination of the development program on D_2O-cooled power reactors.

An experimental program has been proposed that is aimed at development of a suitable fuel element of uranium metal for a D_2O-moderated organic-cooled reactor.

An experimental study was made of the stability of boiling water flow in long coolant channels in parallel, simulating the channels of a nested-tube fuel assembly. Flow instabilities occurred at lower heat fluxes than burnout when three 6-ft-long electrically heated tubes were operated in parallel with boiling flow at 500, 1000, and 1500 psia.

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HEAVY WATER MODERATED POWER REACTORS
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INTRODUCTION

This report is one of a series that summarizes the progress of the Du Pont development program on heavy-water-moderated power reactors. The broad objective of the program is to advance the technology of these reactors so that they could be used in large power stations to generate electricity at fully competitive costs. In the past, program emphasis was placed on reactors that are cooled with liquid D_2O, although much of the program was applicable to other coolants as well. At the direction of the U. S. Atomic Energy Commission, the work on D_2O cooling is being terminated, and a development program on uranium metal fuel for organic-cooled reactors is being considered.

SUMMARY

The Heavy Water Components Test Reactor (HWCTR) was put in standby condition.

An experimental program has been proposed that is aimed at development of a suitable fuel element of uranium metal for a D_2O-moderated organic-cooled reactor. The program will be concentrated on a search for one or more uranium alloys that have enough dimensional stability to operate at a temperature of $500^{\circ}C$ to exposures of ~10,000 MWD/MTU*. The program includes capsule irradiations and fuel assembly irradiations in a Savannah River production reactor and (later on) in an organic-cooled test reactor. Efforts also will be made to develop a metallurgical bond between uranium and aluminum that will permit the operation of bonded aluminum-clad fuel elements at the elevated cladding temperatures (~$450^{\circ}C$) of an organic-cooled reactor.

An experimental study was made of the stability of boiling water flow in long coolant channels in parallel, simulating the channels of a nested-tube fuel assembly. Flow instabilities occurred when three 6-ft-long electrically heated tubes were operated in parallel with boiling flow at 500, 1000, and 1500 psia. The tendency for flow instabilities diminished as the pressure was increased from 500 to 1500 psia and as the coolant mass velocity was increased. At 500 psia, severe flow instabilities occurred at heat fluxes and steam qualities that were much below

* Megawatt-days per metric ton of uranium

those required for heat transfer burnout. At 1500 psia, flow instability did not occur before burnout even at the lowest mass velocity [10^6 lb/(hr)(ft^2)], except when an orifice was in the common effluent piping.

Limited swaging experiments conducted on uranium oxide fuel tubes provided indication that compacting UO_2 in ribbed Zircaloy sheaths should be possible without damaging the ribs during the swaging step. Although further development would be required, these experiments indicate that a feasible concept for spacing fuel tubes in nested-tube assemblies is to attach ribs to the inner sheaths of the tubes by electron beam welding prior to loading and mechanical compaction of the UO_2. In spite of the poor quality of the welded rib tubing that was used in the experiments, the swaging was successful in areas where rib welds were satisfactory. Oxide densities above 91% of theoretical were obtained, and control of tube dimensions during swaging was excellent.

DISCUSSION

I. THE HEAVY WATER COMPONENTS TEST REACTOR (HWCTR)

Operation of the HWCTR was terminated on December 1, 1964 at the direction of the U. S. Atomic Energy Commission (DP-945). During the current report period, the reactor was placed in standby condition, and major pieces of equipment were inspected. The status of the facility and the inspection results are discussed in the following paragraphs.

A. REACTOR STATUS

Subsequent to removal of all fuel and heavy water, the reactor vessel, the two isolated coolant loops, and the primary coolant system were vacuum-dried; these facilities were then filled with dry nitrogen; this atmosphere will be maintained indefinitely to minimize equipment corrosion. The secondary coolant system was drained, and all equipment in the system except the steam generators and purge coolers was left open to the building atmosphere. The generators and purge coolers were slightly pressurized with dry nitrogen. All major auxiliary equipment pieces, such as feedwater pumps, compressors, and turbine drives for pumps, were disassembled and coated with a rust-preventive oil.

After cleanup inside the reactor building, the transferable beta-gamma contamination was less than 500 counts per minute. The radiation levels in the building range from 1 to 25 milliroentgens per hour.

The ventilation units in the reactor and control buildings were shut down, and the circulating water systems were drained and isolated. Selected fans and heaters for the two buildings are being operated continuously to provide humidity control for the preservation of equipment. All electrical systems were de-energized except for those needed to support the equipment preservation program. Heaters in electrical breaker cabinets are energized, and one motor-generator set is operating to provide a trickle charge to emergency power batteries.

Status reports were completed that describe the present condition of the HWCTR, that outline plans for modification that were active at the time of shutdown, and that recommend system modifications which would improve future reactor operation. Other reports are being prepared that summarize the three-year operational history of the reactor.

B. RESULTS OF EQUIPMENT INSPECTIONS

As part of the termination of HWCTR operation, detailed inspections were made of reactor components and process equipment. A description of the various equipment items and their functions is in Reference 1.

1. The Reactor Vessel

The top interior portions of the reactor vessel were inspected with binoculars after the water level was lowered to the top thermal shield. The vertical thermal shield plates and several monitor pins in the core of the reactor were inspected with a borescope. All surfaces were uniformly gray-black in color, and no evidence of corrosion was seen. All nuts were intact, and no cracks were seen on or around them.

2. Zircaloy Bayonet in the Liquid D_2O Loop

The exterior and interior surfaces of the Zircaloy bayonet in the reactor core were inspected with a borescope. No defects or corrosion could be seen. Corrosion coupons simulating the Zircaloy tubing-to-forging weld had shown evidence of "breakaway" corrosion around the weld (DP-945). This weld on the bayonet is located approximately 3 inches from the bottom of the bayonet. To inspect the weld it was necessary to use a 5-foot-long borescope section that was defective, and would not allow adequate focusing. The out-of-focus view of this area showed no evidence of breakaway corrosion.

3. Control Rod Drive and Seal Parts

The drive and seal parts of control rod No. 9 were inspected. When this control rod was thoroughly inspected in April 1963, the following minor items were observed:

(a) Wear on delatch pinion gear teeth.

(b) General rusting of 17-4 PH stainless steel upper extension.

(c) Minor corrosion under O-ring on seal bushing.

The current inspections revealed no new problems, and indicated that the conditions listed above had not worsened since the previous inspection. Most of the 304-L stainless steel parts, including the pinion gear, spline coupling, and rack teeth were dye-checked, and no cracks were detected.

4. Cooling Water System

Pump Seal Coolers and Main Purge Cooler

The pump seal coolers contained large masses of bacterial slime. This was the first observation of slime in the cooling water system since it was cleaned and sterilized in August 1964. A limited view of the tubes in the No. 1 main purge cooler was obtained by removing a blank flange from a vent line. These tubes were also covered with slime deposits.

Steam Valves

One coarse and one fine steam valve were disassembled and inspected. The valve seats, balls, and stems (all stainless steel) were in excellent condition. No discoloration, pits, or defects were apparent. The valve bodies and the inlet and outlet piping (all mild steel) were covered with a thick adherent film of black magnetite, and were in good condition. There was only minor pitting, with most pitting being on the bottom of horizontal pipe where condensate accumulated.

Turbine Drives for Feedwater Pumps

The turbines and their casings were in good condition; they were uniformly covered with magnetite, as was all of the mild steel in the steam system. There was a small amount of chemical deposit in the casing of the No. 2 turbine, but there was no corrosion or pitting beneath the deposit. Most of the turbine blades had been slightly eroded by moist steam from the steam generators, but this condition should not affect any future operation.

Standpipe

The interior of the standpipe was inspected through a manhole after it had been drained. All surfaces were heavily coated with brown sludge that was crusty when dry. The sludge could be easily removed with a wire brush. The metal surfaces were very rough. Thickness measurements indicate that the standpipe corroded at a rate of approximately 7.4 mils per year. The present measured thickness is 200 mils.

Steam Generators

The tubes of both generators were inspected from the handholes which are located just above the tube sheet. The tubes were clean: there was no scale on them, and there was no evidence of the tubercles which were seen at the last inspection in July 1964. The condition of the tubes indicates that the severe oxygen pitting that occurred during the first half of 1964 was arrested by improved oxygen control.

5. Containment Vessel

The third inspection of the containment vessel was made in November 1964. The previous two inspections were made in August 1963 and May 1964. A summary of the inspections is presented in Table I.

In the August 1963 inspection, pitting was observed beneath the adhesive that bonds the polystyrene insulating blocks to the exterior surface of the steel building shell. The maximum pit depth was approximately 15 mils. Although the primer surfaces and the insulation blocks were very wet, the primer had not yet begun to break down except under the patches of adhesive. In May 1964, a slight breakdown of primer was observed, and the maximum pit depth under adhesive patches was 35 mils. At the November 1964 inspection, the primer surfaces were dry, and the insulation blocks were only moist. The breakdown of the primer had progressed only slightly, and the maximum pit depth under adhesive patches was 42 mils. The decreased corrosion rate was attributed to the recent drier and cooler weather.

No measures are being taken now to arrest the corrosion, because it is expected that containment vessel strength will not be impaired seriously in less than 3 to 5 years. Periodic inspections will be conducted to monitor the condition of the vessel.

6. Piping Thickness Measurements

The wall thicknesses of pipe and equipment at selected locations were measured with ultrasonic devices shortly after construction was completed (September 1961) and on two other occasions (April 1963 and December 1964). A summary of results is in Table II. The first two measurements were made with an instrument which had an estimated accuracy of ±5%, and the last measurement was made with an instrument which had an estimated accuracy of ±3%.

In 5 of the 21 locations measured, thickness decreases were greater than the 5% accuracy of the first measurement. Four of these were on equipment that was exposed to the secondary cooling water. The largest decrease (11%) was on the cooling water standpipe, which was exposed to untreated well water for approximately half of its service.

7. Deluge Tank

An inspection of the deluge tank in April 1963 revealed that severe pitting was occurring. The deepest pit was approximately 150 mils, as compared to a tank floor thickness of 375 mils. The tank was cleaned at that time with steel wire brushes to remove loose paint and tubercles, and was refilled with water that contained 1200 ppm chromate inhibitor. An inspection in September 1964 showed that some pitting was still occurring under the primer, but that the rate of pitting had been appreciably reduced by the inhibited water.

The final inspection was made in January 1965, after the tank was sandblasted to remove all primer and tubercles. The largest pit in the tank, which was the one estimated to be 150 mils deep in the first inspection, measured 143 mils deep. Five other pits approximately 140 mils deep were discovered; four of these were on the wall of the entry well. The 4-inch overflow pipe was pitted extensively. The deepest pit was 75 mils, and there were approximately ten pits between 50 and 75 mils deep.

After the inspection and sandblasting, the tank was painted with a new protective primer.

II. POSTIRRADIATION EXAMINATION OF UO_2 FUEL TUBES

Fourteen of the Zircaloy-clad tubes of compacted UO_2 that were under irradiation in the HWCTR when operation was terminated in December were selected for destructive evaluation. This evaluation is part of the orderly termination of the program to develop oxide tubes for D_2O reactors, and the objective is to provide information on the irradiation performance of tubes of various diameters at the highest exposures and power ratings that have been available. All other test fuel will be stored indefinitely in the receiving basin for off-site fuel.

The appearance and dimensions of the tubes were essentially unchanged during irradiation. Free gas within the tubes is being collected and analyzed; subsequently, the core and cladding of some of the tubes will be sectioned and examined metallographically.

A brief description of the objectives and the operating conditions of the four test assemblies in which these tubes were irradiated is shown in Table III.

III. DEVELOPMENT OF WELDED RIB SPACERS FOR UO_2 FUEL TUBES

With the ultimate objective of developing techniques and equipment for attaching spacing ribs to Zircaloy-clad UO_2 fuel tubes by electron beam welding, 0.060-inch-wide Zircaloy ribs were successfully welded to 10 Zircaloy housing tubes (10 feet long x 3.20 inches ID x 0.035-inch wall) for use with the M-3 driver assemblies for the HWCTR. A total of 30 housings have now been ribbed in this manner. Twenty-six of these were selected for possible future use in the HWCTR and are being welded to end fittings. The welding techniques and equipment, previously described in DP-905 and DP-945, produced welds of sufficiently good quality for housing tubes; however, additional development of equipment and techniques will be required for the more exacting task of attaching ribs to fuel element sheath tubes, as described later.

As reported in DP-945, the average rib-circle diameter on the first 20 tubes welded was 0.007 to 0.025 inch greater than the specified nominal rib-circle diameter due to tube "squareness," oversize tubing, and a 0.003- to 0.007-inch hump that formed over each rib during the welding. On the remaining 10 tubes, the rib height was increased 0.003 to 0.007 inch, with the result that the rib circle diameter deviated only $^{+0.003}_{-0.012}$ inch from the nominal dimension.

Deviation of the centerline of the weld from the centerline of the rib along the full 10-foot length was determined by examination of 9 metallurgical samples cut at 1-foot intervals plus 2 samples taken 6 inches from each end. The results from 44 samples, all from the same tube, are shown below:

Typical Alignment of Electron Beam Welds with Ribs on Housing Tube

Number of Samples	Amount Weld Centerline Deviated from Rib Centerline, mils	Typical Section Shown in Figure
7	0-1	1a
8	1-4	1b
8	5-10	
14	11-20	1c
5	21-30	
1	36	1d
1	Did not weld	

The offset between the centerline of the weld and the center of the 60-mil-wide rib is probably due to an accumulation of mechanical factors during electron beam welding, including (1) the radial motion of the rear support truck passing over the uneven table surface, (2) lateral motion of the rib in the mandrel slot, (3) inability of the guide rolls to exert enough pressure to fully compress the tube against the mandrel and thus center it, and (4) possible deviation in the weld beam deflection. Excessive bow of the Zircaloy tube increases the offset to the extent that the guide rolls and mandrel are not able to remove the bow. The tube that was sectioned had a bow of 0.160 inch.

Although the tubes with welded ribs were acceptable for irradiation as housing tubes, the welds would not be satisfactory for swaged UO_2 fuel tubes. To avoid possible disturbance of the fuel core, it is desirable that ribs be attached to fuel sheaths before the oxide is loaded and compacted. The welds must have sufficient penetration to withstand the rigors of the swaging operation and must have no crevices between rib and sheath due to an off-center weld. Crevices such as those shown in Figure 1b, 1c, and 1d would have to be eliminated over the full length of the tube. Possible methods of eliminating them are (1) increase the weld width, (2) increase the accuracy of rib positioning as the rib passes under the electron beam, and (3) improve the dimensional control of the sheath tubing. Additional work, not now planned, would be required to verify a process for welding long ribs on fuel element cladding.

IV. SWAGING OF UO_2 FUEL TUBES WITH INTERNAL RIBS

One of the concepts for fabricating Zircaloy-clad UO_2 fuel tubes with ribs for lateral spacing in fuel assemblies is to attach the ribs to the inner sheath by electron beam welding prior to fuel element fabrication. Inner sheath tubes with ribs welded by the method described in the preceding section would be assembled with outer sheaths, vibratory loaded with oxide, and then swaged over a grooved mandrel. Swaging experiments conducted on two 5-foot-long fuel tubes provided limited indication that, for properly welded-rib sheaths, it should be possible to compact internally ribbed tubes to greater than 90% of theoretical UO_2 density without damaging the ribs. The overall results of the swaging experiments were generally discouraging because of the extremely poor quality of the welded-rib tubing fabricated by an outside vendor, but in the few areas of satisfactory rib welds, the swaging was successful. Poor penetration and weld offset were obvious in all rib welds, and dimensional variations in the sheaths were large--especially near the rib welds, where "humps" occurred (Figure 2). Both tubes required remachining of the rib-circle diameter before a grooved mandrel could be inserted into the tubes. During this operation, one rib of one tube partially broke off and had to be completely machined away.

Normal procedures for oxide tube fabrication were used with no more difficulty than with unribbed tubes. An elongation of the inner sheath of approximately 2.5%, which is the same as for unribbed tubes, resulted from the two swaging passes. The ribs appeared intact when the mandrel was removed, but segments of the ribs broke loose during sectioning because of the poor weld penetration mentioned above. The uranium oxide densities in samples from one tube were in excess of 91% of the theoretical density, and control of internal diameters of the tubes was excellent. The inside diameter of the sheath between the ribs was 1.825 inches ±0.003 inch, and the rib-circle diameter was 1.400 ±0.010 inches.

A photomicrograph of a fully welded portion of a rib after swaging is shown in Figure 3. It is apparent from this figure that the 2.5% elongation of the sheath and rib during swaging did not adversely affect the rib, which was machined so that it did not touch the bottom of the groove in the mandrel during swaging.

Figure 4 illustrates two effects of poorly welded ribs. In this sample, only the right hand corner of the rib was welded to the sheath. The partial weld was not strong enough to prevent separation of the rib from the sheath during swaging. Also, the excessively high rib contacted the bottom of the mandrel groove and caused folds to develop in the sheath tube during swaging.

Because of the program curtailment, no further swaging experiments are planned.

V. URANIUM METAL FUELS FOR ORGANIC-COOLED REACTORS

The Du Pont Company has proposed to the AEC a program aimed at development of suitable fuel elements of uranium metal for a D_2O-moderated organic-cooled reactor (HWOCR). The objective is to establish limits on the operating capabilities of uranium metal in such a reactor so that a reasonably accurate appraisal can be made of the potential of metal fuel in HWOCR service. The Du Pont work would be integrated into the broader program on organic-cooled reactors that is being conducted by other AEC contractors.

To be suitable for use in organic-cooled reactors, uranium must be capable of irradiation to exposures of the order of 10,000 MWD/MTU at a temperature of about 500°C. Unalloyed uranium does not have enough dimensional stability to operate at such a high temperature; therefore, alloying agents must be added. The search for suitable compositions will be concentrated on uranium alloys containing small amounts of Fe, Al, Si, Cr, and Mo in various combinations. A preliminary screening of candidate alloys will be made on the basis of capsule irradiations in a Savannah River production reactor. These irradiations are already underway in connection with another AEC program. In addition, fundamental studies of swelling mechanisms will be conducted to assist in the development of promising new alloy compositions. Concurrently with the capsule tests, fuel assemblies of selected alloys in aluminum cladding will be irradiated with the objective of determining the relative exposure levels at which significant swelling begins.

A design will be developed for a fuel assembly which can be used in a Savannah River reactor to achieve high uranium temperatures at the specific powers that would be experienced in an organic-cooled reactor. Zircaloy-clad fuel elements of the most promising uranium alloys will be fabricated and irradiated to goal exposures of about 10,000 MWD/MTU in this fuel assembly. Uranium temperatures and specific powers that are typical of organic cooling can be achieved in these tests, although cladding temperatures will be too low to simulate an organic reactor. The Savannah River tests will be followed by irradiations of prototype fuel assemblies in an organic-cooled reactor--probably the Canadian WR-1 reactor.

The two leading candidates for fuel cladding in organic reactors are zirconium and aluminum. No fundamental fabrication development is necessary for Zr-clad uranium because the coextrusion process is well developed for these materials. However, existing fabrication processes for cladding uranium in aluminum probably are not suitable because the Al-Ni-U bonding system employed in these processes will not withstand the elevated cladding temperature ($\sim 450^{\circ}C$) of an organic reactor. The Du Pont program includes an attempt to devise a U-Al bonding system that is adequate for high-temperature service. Initially, experimental development of a barrier layer that will prevent diffusion of the aluminum will be undertaken. If any promising bonding systems are discovered, development will be started on fuel fabrication processes that incorporate these systems. The fabrication development will include fuel closure methods by means of which end plugs of Aluminum Powder Material can be used with aluminum-base cladding.

VI. STABILITY OF BOILING WATER FLOW IN PARALLEL CHANNELS

The stability of forced flow of boiling water in the parallel coolant channels of a nested-tube fuel assembly was under investigation at the Columbia University Engineering Center when the Du Pont program on D_2O-cooled power reactors was terminated in late 1964. The objectives were to determine (1) the conditions for flow instability, (2) the effect of the resultant flow oscillations on the burnout heat flux, and (3) the channel orificing requirements to insure stable flow and high burnout heat flux. Preliminary results of the investigation were reported in DP-895. Additional data obtained prior to the termination of the program are discussed in the following paragraphs.

In the preliminary test reported in DP-895, the heat flux at burnout was determined for an assembly consisting of three 6-ft-long tubular channels that were operated in parallel and were closely connected to common inlet and outlet plenums. The channels were heated electrically. The pressure for the tests was 1500 psig. The burnout heat flux was only zero to 10% lower than that of single-channel assemblies. It was not possible to measure the flows to the individual tubes, however, and the coolant channels were perfectly matched in power and geometry. Additional results have now been obtained with a second test assembly in which the flow to each tube was measured and a small imbalance in channel power existed. This assembly was operated at 500, 1000, and 1500 psia. The tests demonstrated that severe instability of the flow can occur within an assembly of long channels in parallel even though the total flow to the assembly is steady. Conditions with severe flow instability were not pursued to burnout. However, where burnout was reached with some degree of flow instability, the burnout heat flux was higher than for the single-channel reference. This tendency for flow instability diminished upon increasing the pressure from 500 to 1500 psia and upon increasing the mass velocity from 1 to 2 million lb per $(hr)(ft^2)$ and higher.

The nominal tube dimensions for this second test assembly were 0.5-in. ID x 6.33-ft long. The heat flux limits for single tubes of this description operating alone were presented in DP-895. Turbine flow meters measured the water flow through each tube and the total flow; all flow measurements were recorded on a high-speed oscillograph. Each tube was fitted with a burnout detector, which was an electrical bridge arrangement with greatest sensitivity to changes in heater temperature in the downstream final foot of heated length.

For an imbalance in channel power, the wall thickness of one tube was larger at the expense of the tube ID (0.493-in. ID vs. 0.503-in. ID for the other two). The imbalance in channel power was about 9%, the power being higher for the thicker tube. At power with bulk boiling the imbalance in coolant mass velocity and exit steam quality was magnified, particularly at lower pressure. For example, the following channel conditions existed in one run at 500 psia:

Imbalance in Mass Velocity and Exit Quality

	Tube 1	Tube 2	Tube 3	Assembly Average
Heat flux, 10^6 pcu/(hr)(ft^2)	0.283	0.283	0.310	0.292
Mass velocity, 10^6 lb/(hr)(ft^2)	2.43	2.33	0.91	2.05[a]
Exit quality, %	0.00	0.71	33.1	3.88
Boiling length, ft	0.00	0.26	4.21	-

(a) Based on turbine meter for total flow to the assembly.

Imbalance is undoubtedly a factor contributing to flow instability. The extent of the power imbalance in this particular test assembly was not unrealistic for a power reactor.

In the conduct of the runs, the flow and inlet temperature were established first. The power was then increased in steps until either a heat transfer burnout indication or a rapidly increasing fluctuation in the flow occurred in one of the tubes, at which time the power was reduced. Unfortunately, operation with flow instability was not continued to determine the power capability, though this item was in the future program. Approximately one-half of the data points showed flow instability occurring before burnout. The flow fluctuation was largest in the tube (No. 3) having the highest power, and the fluctuation in this tube was 180° out of phase with the fluctuation in the other two tubes, as shown in Figure 5. The instability in flow often seemed to develop spontaneously some time after the last step increase in power. There was no indication of a fluctuation in the total flow to the assembly; the phenomenon seemed to be strictly hydraulic interaction among the channels. The minimum in the flow frequently reached zero before the power could be shut off.

Conditions at which either a heat transfer burnout or an instability in flow was experienced are given in Table IV. Two experimental setups were used: with and without an orifice restriction in the effluent piping for the combined streams. The purpose of the orifice restriction was to simulate the effect of the connector piping from a reactor fuel assembly to the effluent coolant header. The limiting heat fluxes are plotted as a function of quality in Figure 6 for pressures of 500, 1000, and 1500 psia, respectively, at mass velocities of 1 and 2 million lb/(hr)(ft^2) ±15%. Severe flow instability is indicated by open points, heat transfer burnout by solid points. Runs with the orifice in the common effluent piping are indicated by horizontal lines through the points. The plotted conditions are those in the tube in which the severe oscillation or burnout occurred. The assembly average conditions, as computed from the measurements of total flow, are plotted similarly in Figure 7. For reference, the characteristics for the burnout heat flux in single tubes are given in Figures 6 and 7 as curves which fitted the single-tube data very closely (DP-895).

The runs plotted in Figure 6 are not necessarily the same as those in Figure 7 because of the spread that developed in the mass velocity for the individual tubes. Because of this spread, the comparison of assembly-average conditions (Figure 7) with the single-tube reference curves is less meaningful than the comparison from Figure 6. The picture is essentially the same by either presentation, however. The following conclusions were reached:

(1) Burnout conditions were never achieved in operation at 500 psia; severe flow instability occurred at heat fluxes and qualities much below those required for burnout.

(2) Flow instability occurred closer to conditions for burnout as the pressure was increased, if it occurred at all.

(3) At 1000 psia, flow instability did not occur before burnout at the higher mass velocity of 2 million lb/(hr)(ft^2), except in the one instance (which was duplicated) with an orifice in the common effluent piping.

(4) At 1500 psia, flow instability did not occur before burnout even at 1 million lb/(hr)(ft^2) except when an orifice was in the common effluent piping.

(5) The burnout heat flux was generally higher with this second 3-tube assembly than was observed with the single-tube assemblies, and also was generally higher than in the first 3-tube assembly (Figure 8). This gain may be the result of a more labile flow condition with enthalpy imbalance for channels in parallel.

(6) The orifice in the common effluent piping, while contributing to flow instability, did not by itself seem to affect adversely the power limit (severe flow instability or burnout). In fact, the heat fluxes and qualities in runs with the effluent orifice were among the highest attained.

(7) In one run (Run 52.1, Table IV) with an orifice in the common effluent piping, the heat flux at burnout of 543,000 pcu/(hr)(ft^2) was 40% higher than the reference for single-tube assemblies. The conditions were 1000 psia, 2 million lb/(hr)(ft^2), and 20% exit quality. Thus, it appears that a labile flow condition can enhance the power capability.

TABLE I

Summary of Containment Vessel Inspections

Date	Max. Pit Depth under Adhesive, mils	Max. Pit Growth Rate, mils/month	Primer Condition	Moisture
Aug 1963	15		No primer breakdown	Primer surfaces and blocks very wet
		2.2		
May 1964	35		Slight primer breakdown; pits <5 mils	Primer surfaces and blocks very wet
		1.2		
Nov 1964	42		Slight primer breakdown; pits <5 mils	Primer surfaces dry, blocks moist

TABLE II

Summary of Thickness Measurements on HWCTR Equipment

Equipment	Material	Original Nominal Thickness, in.	Thickness Measurements, in. 9-6-61	4-15-63	12-18-64	Summary of Changes from 1st Measurement: Increase >5%	None (Within 5%)	Decrease >5%
Steam generator head	Mild steel	2.375 min.	2.50	2.50	2.50		x	
10" elbow in generator D_2O outlet	Mild steel	0.718	0.700	0.750	0.750	x		
10" elbow in generator D_2O inlet	Mild steel	0.718	0.720	0.720	0.750		x	
10" elbow in #1 pump suction line	Mild steel	0.718	0.800	0.760	0.780		x	
10" straight section upstream of elbow above	Mild steel	0.718	0.780	0.780	0.780		x	
No. 1 purge cooler head	Mild steel	2.00	2.00	2.10	2.00		x	
No. 2 purge cooler head	Mild steel	2.00	2.00	2.00	2.00		x	
No. 1 purge cooler shell	Mild steel	0.375	0.400	0.390	0.385		x	
No. 2 purge cooler shell	Mild steel	0.375	0.400	0.390	0.380			x(5%)
Bottom of main storage tank	Mild steel	0.375	0.355	0.360	0.350		x	
Side of main storage tank	Mild steel	0.375	0.360	0.375	0.370		x	
Hold tank (gas section)	Mild steel	0.375	0.380	0.380	0.360			x(5%)
Seal pot (gas section)	Mild steel	0.375	0.400	0.410	0.400		x	
Seal pot (liquid section)	Mild steel	0.375	0.390	0.400	0.380		x	
Flash tank (liquid section)	Mild steel	0.187	0.185	0.180	0.175			x(5%)
Cooling water head tank	Mild steel	0.375	0.360	0.375	0.340			x(6%)
Cooling water standpipe	Mild steel	0.250	0.224	0.210	0.200			x(11%)
Liquid loop heat exchanger shell	316 SS	0.875	0.850	0.860	0.900	x		
Purification collection tank	304 SS	0.187	0.181	0.220	0.200	x		
Flash tank, near inlet pipe	304 SS	0.187	0.185	0.180	0.180		x	
					Totals	3	12	5

TABLE III

Assemblies of UO_2 Fuel Tubes
Selected for Postirradiation Examination

Assembly Designation	Purpose of Test	Maximum $\int k d\theta$, watts/cm	Maximum Exposure, MWD/MTU
SOT-1-2	Demonstrate behavior of 2.1-inch-diameter UO_2 tubes to high exposures at moderate thermal ratings	25	17,300
SOT-6-2 SOT-9-2	Demonstrate behavior of intermediate-size (2.5-inch diameter) UO_2 tubes of reference fuel assembly described in DP-885	30 40	5,000 4,000
SOT-8-3	Demonstrate behavior of largest UO_2 tubes (3.7-inch diameter) of reference fuel assembly described in DP-885	30	4,300

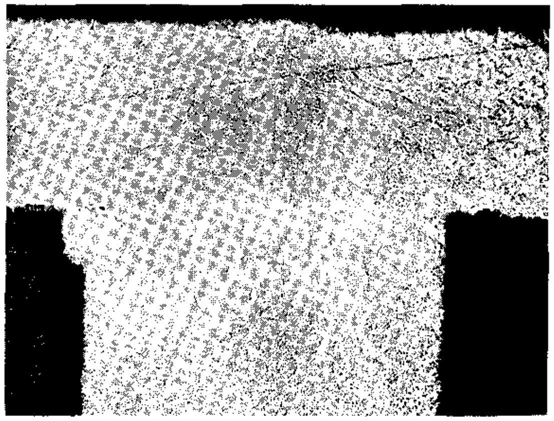
TABLE IV

Burnout Heat Flux and Flow Instability Limits for Three Tube Assembly

ID: Tubes 1 and 2, 0.503 in.; Tube 3, 0.493 in. Heated length, 76 in.

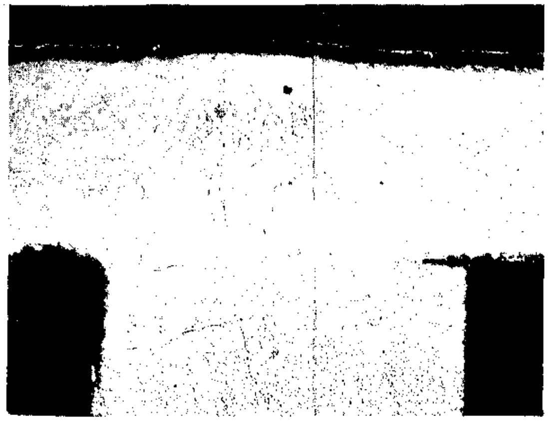
Run No.	Pressure, psia	Inlet Temp, °C	Inlet Subcooling, °C	Power, kw	Heat Flux, 10^6 pcu/(hr)(ft²)			Mass Velocity, 10^6 lb/(hr)(ft²)				Exit Quality, wt %				Limit		Pressure Differential Across Orifice in Exit Piping, psi
					Tubes 1 and 2	Tube 3	Overall Average	Tube 1	Tube 2	Tube 3	Overall Average(a)	Tube 1	Tube 2	Tube 3	Overall Average	Burnout Tube No.	Flow Instability Tube No.	
26	500	226	16	200	.148	.161	.152	1.06	1.27	1.01	1.10	15.8	12.5	19.2	15.7	-	3	No orifice
27	500	206	36	223	.165	.181	.171	.99	1.12	.79	1.00	14.6	11.7	24.1	15.2	-	3	No orifice
28	500	184	58	257	.190	.208	.196	1.00	1.48	.70	1.03	12.6	3.6	28.5	12.6	-	3	No orifice
29	500	228	14	394	.291	.318	.301	1.93	2.32	1.95	2.09	18.0	14.4	20.3	17.1	-	3	No orifice
30	500	205	37	431	.318	.348	.329	1.81	2.47	1.76	2.06	15.7	9.0	19.4	13.5	-	3	No orifice
31	500	183	59	381	.281	.307	.291	2.44	2.70	1.04	2.06	1.3	-0.2	28.2	5.1	-	3	No orifice
32	500	227	14	475	.351	.383	.362	2.51	2.69	2.49	2.55	16.4	15.0	18.8	16.7	-	3	No orifice
33	500	205	37	554	.409	.447	.423	2.56	3.09	2.35	2.61	13.5	9.5	18.4	13.9	-	3	No orifice
34	500	182	60	453	.335	.366	.346	3.25	2.96	1.34	2.32	-0.6	0.9	24.7	4.4	-	3	No orifice
56	500	227	15	436	.322	.352	.333	2.39	2.57	2.24	2.56	15.5	14.1	19.1	14.8	-	3	Not recorded
57	500	201	41	498	.368	.402	.380	2.32	2.86	1.94	2.55	12.1	7.8	19.8	10.8	-	3	22.9
58	500	178	64	458	.338	.370	.350	3.04	2.91	1.15	2.55	-0.3	0.4	31.1	3.4	-	3	7.5
59	500	226	16	361	.267	.292	.276	1.79	2.03	1.71	2.05	17.3	14.7	20.9	15.2	-	3	16.6
60	500	204	38	417	.308	.336	.318	1.81	2.25	1.65	2.04	14.7	10.0	20.3	12.8	-	3	13.4
61	500	177	65	383	.283	.309	.292	2.43	2.33	.91	2.05	0.0	0.7	33.1	3.9	-	3	Not recorded
62	500	225	17	171	.127	.138	.131	.92	1.03	.87	1.03	15.3	13.3	18.9	13.9	-	3	Not recorded
63	500	208	34	212	.157	.171	.162	.95	1.06	.84	1.03	14.9	12.4	20.9	13.8	-	3	Not recorded
1	1000	266	19	357	.264	.288	.273	1.01	1.08	.98	1.03	37.5	34.8	44.3	38.3	-	3	No orifice
2	1000	246	39	367	.272	.297	.281	1.03	1.12	.98	1.07	31.1	27.8	38.7	31.0	-	3	No orifice
3	1000	224	61	372	.275	.300	.284	.91	1.03	.79	1.00	31.0	25.0	45.2	28.4	-	3	No orifice
4	1000	203	82	388	.287	.313	.296	.94	1.07	.72	.95	25.2	19.2	48.5	26.3	-	3	No orifice
5	1000	181	104	414	.306	.334	.316	.97	1.16	.71	1.02	20.4	11.5	48.2	19.8	-	3	No orifice
6	1000	270	15	449	.332	.362	.343	1.84	2.01	1.96	1.99	25.1	22.6	26.7	23.9	3	-	No orifice
7	1000	248	37	488	.361	.394	.372	2.08	2.16	2.09	2.13	16.8	15.6	19.9	17.0	3	-	No orifice
8	1000	229	56	522	.386	.421	.398	2.02	2.14	1.96	2.09	13.7	11.9	18.6	13.8	3	-	No orifice
9	1000	207	78	551	.407	.445	.421	2.06	2.18	1.73	2.01	8.2	6.3	19.2	10.2	3	-	No orifice
10	1000	183	102	572	.423	.462	.437	2.41	2.09	1.48	2.02	-2.4	2.1	21.7	4.5	3	-	No orifice
11	1000	269	16	469	.347	.379	.358	2.52	2.69	2.60	2.58	17.9	16.4	19.7	18.1	3	-	No orifice
12	1000	249	36	496	.367	.401	.378	2.56	2.62	2.56	2.66	12.2	11.6	15.0	12.2	3	-	No orifice
13	1000	227	58	555	.411	.448	.424	2.82	2.91	2.57	2.77	5.5	4.7	11.0	6.9	3	-	No orifice
14	1000	206	79	605	.447	.488	.462	3.00	2.81	2.74	2.78	-0.3	1.4	5.2	2.7	3	-	No orifice
15	1000	187	98	716	.529	.578	.546	3.16	2.95	2.78	3.03	-2.7	-0.7	4.8	-0.5	3	-	No orifice
16	1000	269	16	426	.314	.344	.325	1.48	1.51	1.46	1.50	30.1	29.5	34.8	31.2	3	-	No orifice
17	1000	249	36	456	.337	.368	.348	1.49	1.66	1.52	1.52	26.0	22.0	29.4	26.6	3	-	No orifice
18	1000	227	58	487	.360	.393	.372	1.46	1.52	1.43	1.52	22.6	20.9	28.3	22.4	3	-	No orifice
19	1000	204	81	519	.384	.419	.397	1.44	1.66	1.34	1.54	18.9	13.0	27.8	17.7	3	-	No orifice
22	1000	274	11	292	.216	.236	.223	.86	.91	.81	.88	38.6	36.1	46.3	39.1	-	3	No orifice
24	1000	226	59	282	.208	.227	.215	.97	1.12	.89	.97	16.9	12.0	24.8	18.1	-	3	No orifice
45	1000	272	13	484	.358	.391	.369	1.98	2.01	1.98	2.11	25.9	25.4	29.4	25.0	3	-	16.6
46	1000	232	53	563	.416	.454	.429	1.92	2.06	1.85	2.04	19.1	16.7	24.8	18.3	-	3	Not recorded
47	1000	249	36	513	.379	.414	.391	1.91	2.10	1.92	2.04	21.3	18.3	24.9	20.3	3	-	Not recorded
48	1000	234	51	564	.417	.456	.431	1.98	2.16	1.89	2.08	18.7	15.8	24.5	18.1	-	3	Not recorded
49	1000	205	80	600	.443	.484	.458	2.03	2.19	1.57	2.04	11.1	8.5	27.4	12.4	3	-	Not recorded
50	1000	273	12	513	.379	.414	.392	2.40	2.61	2.43	2.58	22.6	20.5	25.2	21.7	3	-	22.7
51	1000	232	53	613	.453	.495	.468	2.47	2.61	2.30	2.56	13.6	11.9	19.7	13.6	2	-	Not recorded
52	1000	203	82	672	.497	.543	.513	2.95	2.57	2.03	2.57	2.3	6.5	19.8	7.6	3	-	9.4
53	1000	273	12	385	.284	.311	.294	1.05	1.08	0.98	1.07	41.4	40.2	50.1	42.4	-	3	6.6
54	1000	231	54	374	.277	.302	.286	1.03	1.17	0.91	1.07	27.6	22.0	39.5	27.6	-	3	3.4
55	1000	204	81	401	.296	.323	.306	1.06	1.06	0.79	1.06	21.4	21.2	44.7	23.1	-	3	3.4
67	1000	272	13	564	.417	.455	.431	4.03	4.31	3.78	4.10	13.0	11.9	16.3	13.4	2	-	Not recorded
35	1500	288	25	333	.246	.268	.254	1.06	1.04	1.03	1.03	34.3	35.5	41.3	37.3	3	-	No orifice
36	1500	260	53	379	.281	.306	.289	1.03	1.03	0.99	1.02	31.0	31.0	39.7	33.7	3	-	No orifice
37	1500	233	80	412	.304	.332	.314	1.08	1.02	1.01	1.06	23.0	26.2	34.0	26.4	3	-	No orifice
38	1500	206	107	442	.326	.357	.337	1.13	1.13	0.95	1.07	15.0	15.0	33.4	20.3	3	-	No orifice
39	1500	285	28	415	.307	.335	.317	2.10	2.04	2.02	2.10	16.3	17.1	20.8	17.3	2	-	No orifice
40	1500	259	54	472	.349	.381	.361	2.13	2.01	1.98	2.05	9.5	11.3	15.8	11.9	3	-	No orifice
41	1500	232	81	528	.391	.427	.403	2.17	1.96	1.86	1.99	2.6	6.4	13.2	7.2	3	-	No orifice
42	1500	206	107	571	.422	.461	.436	2.10	2.01	1.92	2.04	-2.5	-0.7	6.2	0.2	3	-	No orifice
43	1500	287	26	445	.329	.359	.339	2.59	2.51	2.57	2.54	13.5	14.2	16.6	14.8	2	-	No orifice
44	1500	260	53	509	.376	.411	.388	2.70	2.50	2.49	2.60	5.1	7.3	10.8	7.2	3	-	No orifice
64	1500	283	30	342	.253	.276	.261	0.98	0.99	0.97	1.07	37.5	36.8	43.8	34.7	-	3	Not recorded
65	1500	261	52	384	.284	.310	.293	0.94	0.96	0.93	1.04	36.9	35.8	44.9	33.7	-	3	Not recorded
66	1500	233	80	432	.319	.348	.329	0.98	0.99	0.94	1.06	31.9	31.1	41.9	29.2	3(b)	-	Not recorded

(a) Overall average flow is based on the measurement of total flow to the 3-tube assembly.
(b) Flow instability was imminent at the time that heat transfer burnout was indicated by the burnout detector.



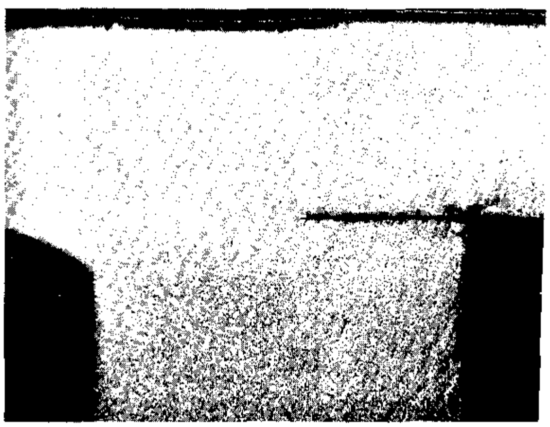
30X

a. No weld offset



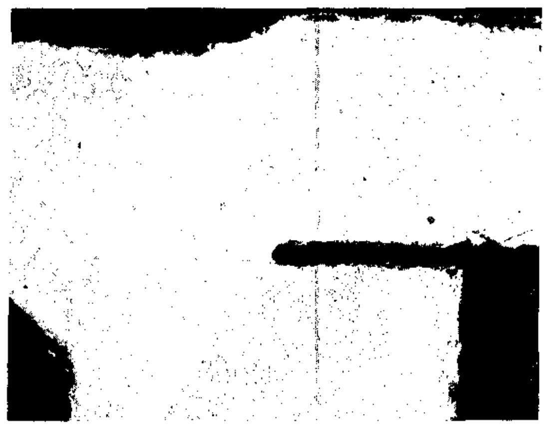
30X

b. 0.004 - inch weld offset



30X

c. 0.020 - inch weld offset

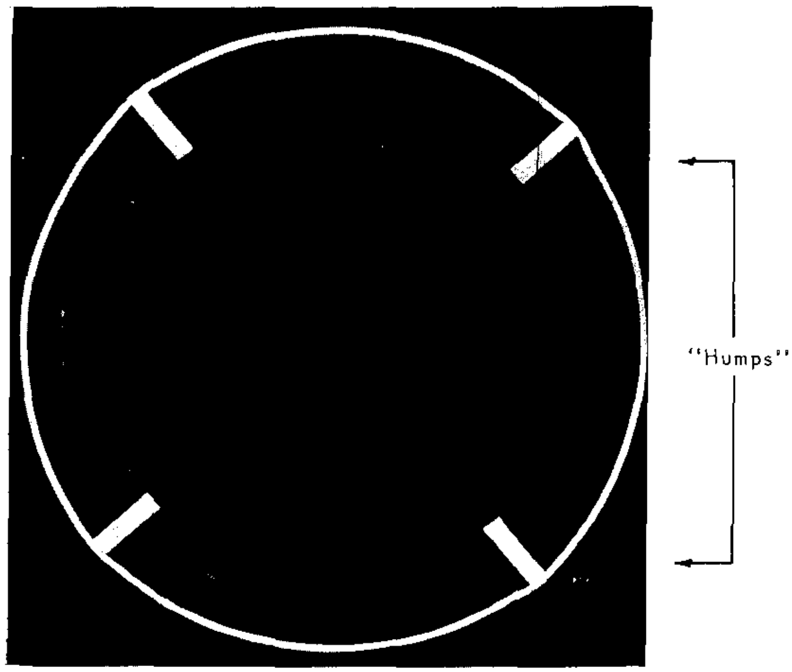


30X

d. 0.036 - inch weld offset

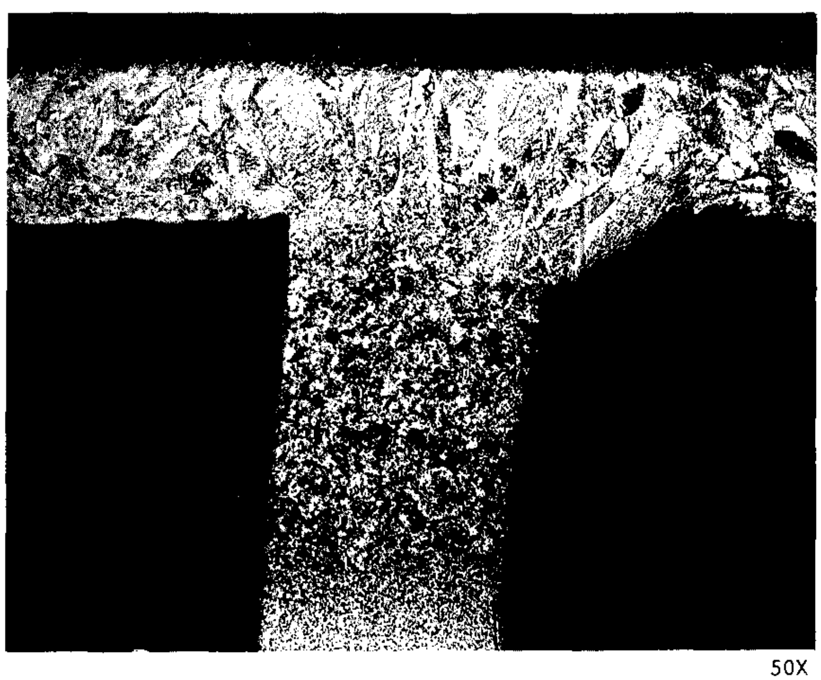
FIG. 1 CROSS SECTION OF WELD BETWEEN RIB AND HOUSING TUBE

0.060 - inch - wide Zircaloy ribs attached to Zircaloy housing tube (0.035 - inch wall) by electron beam welding



1.8X

FIG. 2 ZIRCALOY SHEATH WITH WELDED RIBS BEFORE UO_2 LOADING AND SWAGING 1.840-in. ID x 0.022-in. wall; 0.060-in. -wide ribs



50X

FIG. 3 ZIRCALOY SHEATH WITH FULLY WELDED RIB AFTER SWAGING

50X

FIG. 4 ZIRCALOY SHEATH WITH INCOMPLETE WELD AFTER SWAGING

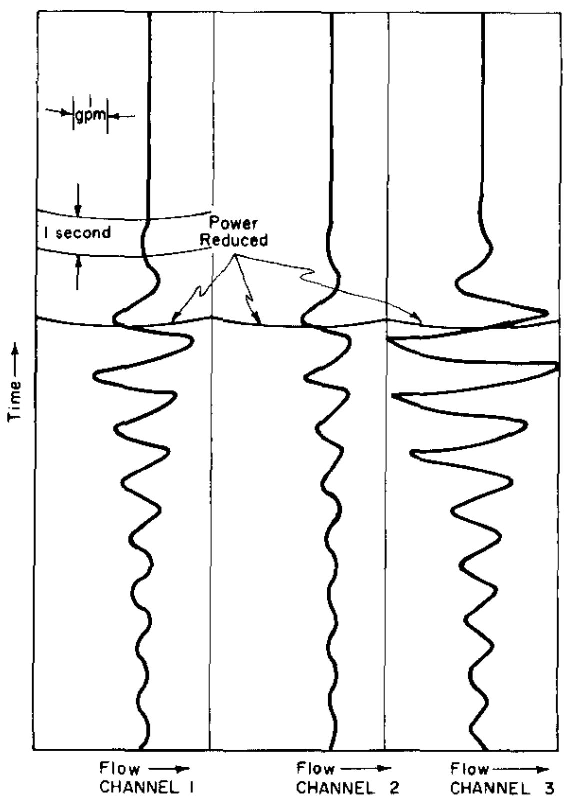


FIG. 5 BOILING FLOW INSTABILITY IN COOLANT CHANNELS OPERATED IN PARALLEL Steady-state conditions with respect to power and total coolant flow

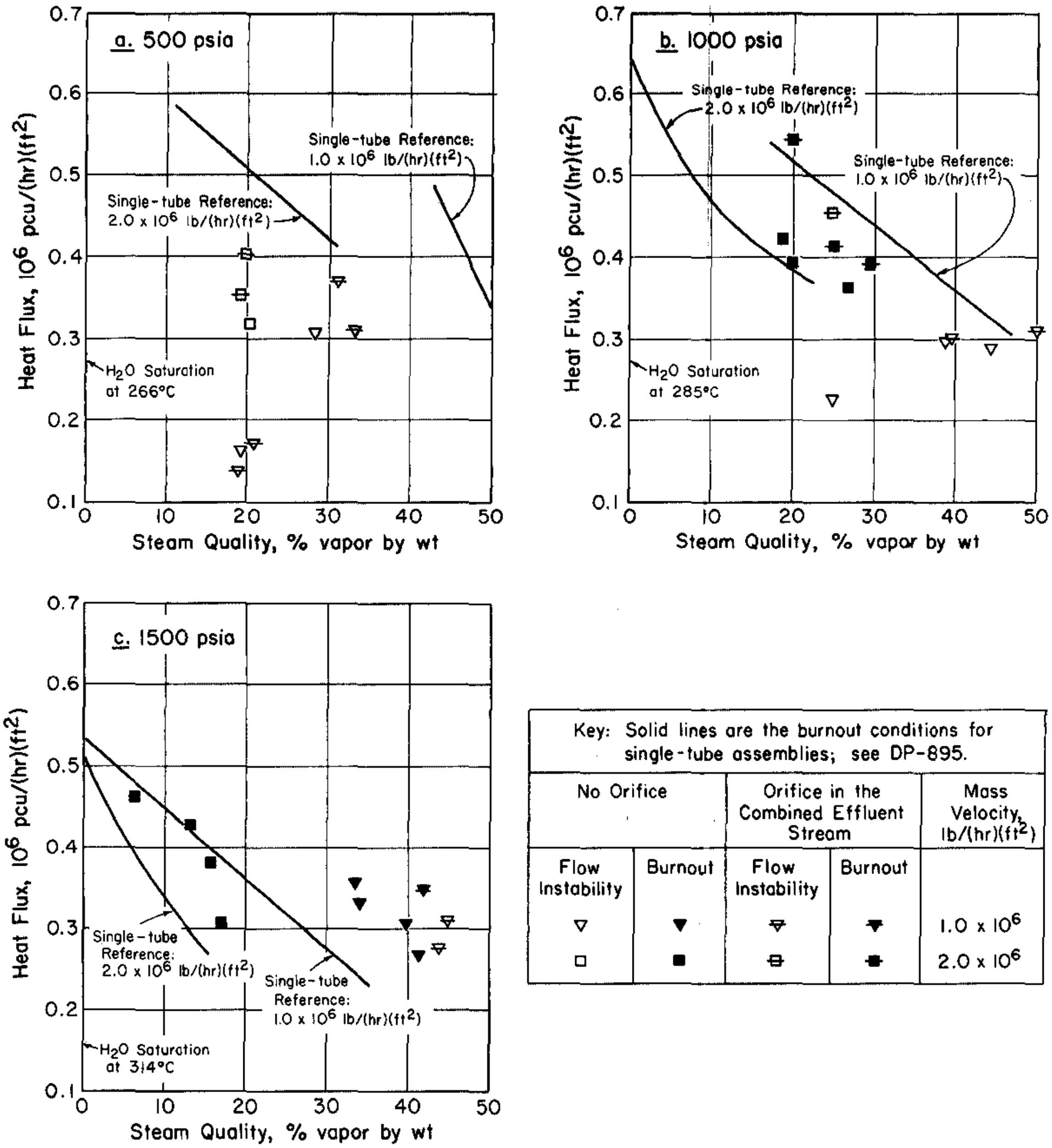
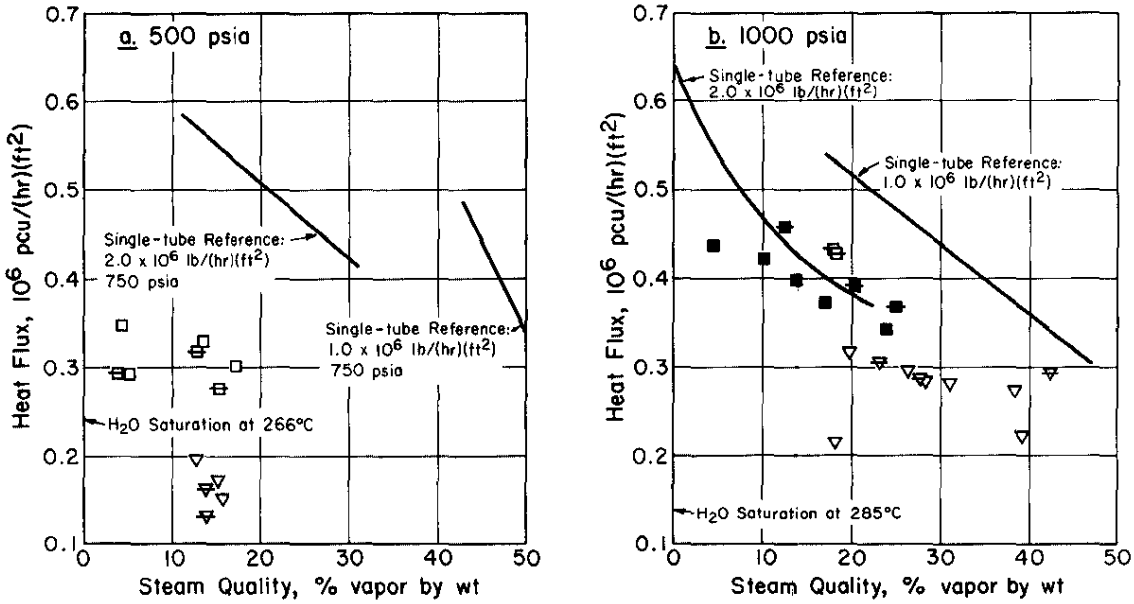
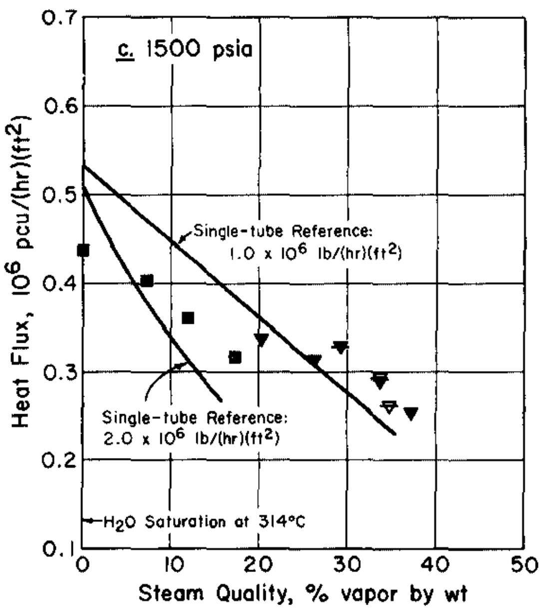


FIG. 6 BURNOUT AND SEVERE FLOW INSTABILITY FOR THREE TUBES IN PARALLEL (Conditions in the Limiting Tube)





Key: Solid lines are the burnout conditions for single-tube assemblies; see DP-895.				
No Orifice		Orifice in the Combined Effluent Stream		Mass Velocity, lb/(hr)(ft²)
Flow Instability	Burnout	Flow Instability	Burnout	
▽	▼	▽ (with bar)	▼ (with bar)	1.0 x 10⁶
□	■	□ (with bar)	■ (with bar)	2.0 x 10⁶

FIG. 7 BURNOUT AND SEVERE FLOW INSTABILITY FOR THREE TUBES IN PARALLEL (Average Conditions for the Assembly)

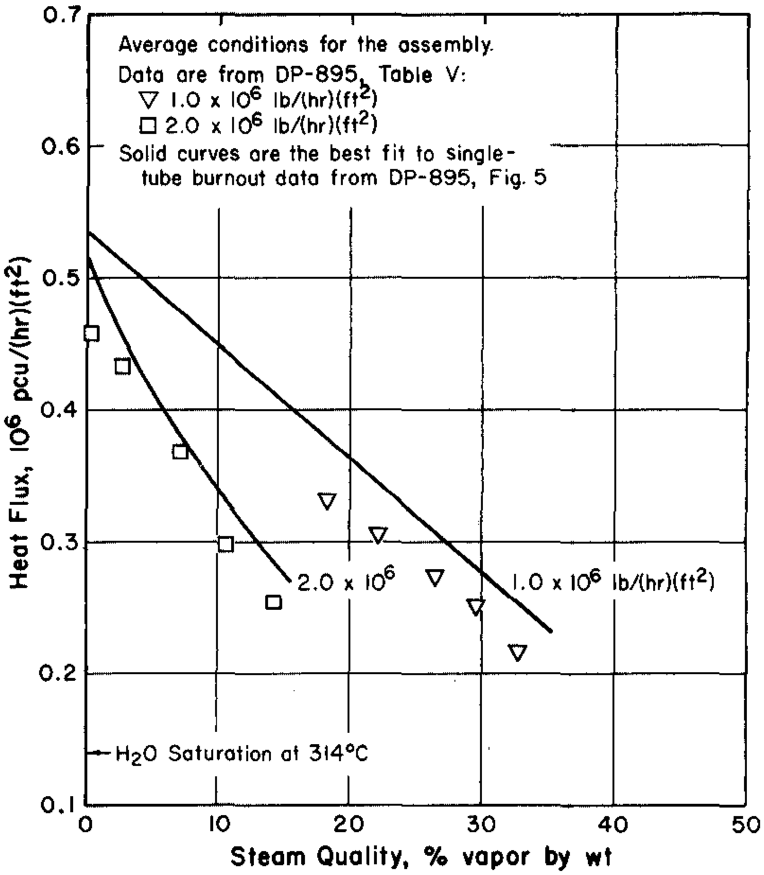


FIG. 8 BURNOUT FOR FIRST ASSEMBLY OF THREE TUBES IN PARALLEL AT 1500 PSIA

BIBLIOGRAPHY

1. Arnett, L. M., et al. Final Hazards Evaluation of the Heavy Water Components Test Reactor (HWCTR). USAEC Report DP-600, E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, S. C. (1962).

2. Previous progress reports in this series are:

DP-232	DP-395	DP-485	DP-575	DP-665	DP-755	DP-855
DP-245	DP-405	DP-495	DP-585	DP-675	DP-765	DP-865
DP-265	DP-415	DP-505	DP-595	DP-685	DP-775	DP-875
DP-285	DP-425	DP-515	DP-605	DP-695	DP-785	DP-885
DP-295	DP-435	DP-525	DP-615	DP-705	DP-795	DP-895
DP-315	DP-445	DP-535	DP-625	DP-715	DP-805	DP-905
DP-345	DP-455	DP-545	DP-635	DP-725	DP-815	DP-915
DP-375	DP-465	DP-555	DP-645	DP-735	DP-825	DP-925
DP-385	DP-475	DP-565	DP-655	DP-745	DP-835	DP-935
					DP-845	DP-945