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TESTS OF THE EFFECT OF SCALE BUILD-UP
ON HEAT TRANSFER USING UNTREATED
WATER UNDER CONDITIONS TYPICAL
OF THE ETS-1 EXHAUST DUCT

D. R. Dickinson

March 1968

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OF SCALE BUILD-UP ON HEAT TRANSFER
USING UNTREATED WATER UNDER CONDITIONS TYPICAL
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By

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TESTS OF THE EFFECT
OF SCALE BUILD-UP ON HEAT TRANSFER
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INTRODUCTION

This report describes tests conducted for the Space Nuclear Propulsion Office to determine whether a thermally insulating scale deposit would build up if untreated well water were used in place of deionized water for cooling the ETS-1 exhaust duct.

The NERVA engine test stand (ETS-1) has a large duct to carry off the hot exhaust hydrogen from the nuclear rocket engine being tested. In order to prevent overheating, water is passed in single-pass flow through a large number of flow passages which form the wall of the duct. There is a strong incentive to use untreated well water as the coolant in order to save the cost of deionization. However, this raises the possibility of scale deposition on the heated surface which could interfere with heat transfer and lead to an excessive duct wall temperature. Scaling data did not exist for the high heat fluxes (up to 1.35×10^6 Btu/hr ft²), high water velocities (35 ft/sec), or short time of operation (about 3 hr total) expected in the ETS-1 exhaust duct. Therefore, testing under these conditions was necessary to determine whether scale build-up would be a problem with untreated water.

SUMMARY AND CONCLUSIONS

To determine the possibility of scale formation in the coolant passages of the NERVA ETS-1 hydrogen exhaust duct tests were conducted in an electrically heated test section representative of one of the flow passages, using well water from Jackass Flats, Nevada.

Test conditions were:

- 1,352,000 Btu/hr ft² heat flux and 35 ft/sec water velocity for 243 min.
- 1,664,000 Btu/hr ft² and 35 ft/sec for 110 min.
- 159,000 Btu/hr ft² and 3.5 ft/sec for 110 min.

Little or no rise in wall temperature attributable to scale deposition was observed. Visual inspection at the end of the test showed a clean surface except for a light deposit at the upstream end. No corrosion of the stainless steel tubing occurred.

At most, only a slight increase in surface temperature due to scale deposition will occur if untreated water is used to cool the ETS-1 exhaust duct, provided conditions are not more severe than in these tests.

DESCRIPTION OF TEST

The test conditions were chosen to match as closely as possible the most severe conditions expected in the ETS-1 exhaust duct.

The test section was fabricated from Type 321 stainless steel seamless tubing. Its dimensions were:

Outside diameter	0.809 in.
Wall	0.031 in.
Inside diameter	0.747 in.
Upstream approach length	48 in.
Heated length	60 in.
Downstream length	12 in.

The variation in wall thickness, as determined by eddy-current measurements, was less than $\pm 3\%$.

The test section was heated by passing dc electric current through the metal wall of the tubing. Copper sleeves were brazed to the tubing over the full circumference at either end of the heated length, through which current was supplied from a bank of rectifiers. Holes, 1/16 in. in diameter, were drilled through the copper sleeve and steel wall to serve as pressure taps; two taps were located 60.6 in. apart at either

end of the heated length. The heated and downstream portions of the test section were covered with 2 in. of magnesia insulation to prevent heat loss.

The wall temperature was measured by 14 thermocouples in two rows 180° apart and spaced axially at 8-in. intervals.* The end of the 1/16 in. O. D. thermocouple sheath was welded to the outside surface of the tubing; the thermocouple junction was insulated. These thermocouples were read out through a digital print-out system and on continuous strip charts. Two other thermocouples were used to measure the inlet and outlet water temperatures.

The test facility is shown schematically in Figure 1. Water flowed from a 3,000 gallon head tank, through a small inlet heat exchanger, the pump, flow control valve, and a turbine flow meter to the heated test section. The water then flowed through the main heat exchanger, a pressure reduction valve, and back to the tank. All equipment was of stainless steel, except the tank which had recently been cleaned and painted, and the return line to the tank which was rubber hose.

Pressure and flow were controlled by the valves upstream and downstream of the test section; once set, flow and pressure remained quite constant. Heat flux was controlled by manually varying the voltage supplied to the test section from the rectifiers. Power also remained nearly constant, once set. Inlet temperatures was controlled by manual adjustment of the inlet heat exchanger. The inlet water temperature varied several degrees during each test.

A supply of water from the well at Jackass Flats, Nevada, which supplies water for cooling the ETS-1, was trucked to Battelle-Northwest for this test. Before testing with well water, the entire system was flushed by recirculating deionized water for two hours. Analyses of this water showed good purity; minerals were not being picked up from

* Two of these thermocouples gave questionable readings and had abnormally low resistance to ground; their readings were ignored in the data analysis.

FIGURE 1. Flow Diagram

the piping surfaces. The system was then refilled with fresh deionized water and run at full power to measure temperatures with no scale. Finally, the system was flushed several times with recirculating well water.

Tests for scale deposition with well water were made under three sets of conditions which are described in detail in Table I. The first was under normal conditions; i. e., the most severe conditions expected in normal operation of the ETS-1. The second was with a heat flux 23% higher than this. The third was with a low flow rate and low heat flux, corresponding to conditions which may be encountered in the tail-off of some tests in the ETS-1. The first test was divided into several cycles of 5, 10, and 20 min duration, between which the heat flux was reduced to near zero and then raised to its normal value. The exact sequence and duration of these cycles are shown in Figure 2. All increases and reductions in heat flux were made at an approximately linear rate over a period of about one minute. The second and third tests were each made up of one 60-min and one 30-min cycle. At the conclusion of the third (low flow) test, another 20-min cycle at the highest heat flux was run.

Water samples were taken at intervals of about two hours during the test. Other samples were taken from the well at the time the water supply for these tests was withdrawn and at the time the tank in the test facility was filled. Chemical analyses of these samples showed that the concentrations of minerals dissolved in the water did not change significantly during transport of the water from Nevada or during the test. Details of these analyses are shown in Table II.

The measured rise in bulk water temperature agreed closely with that calculated from the power input and flow, indicating that heat losses were negligible.

TABLE I. Test Conditions

	<u>Deionized Water</u>	<u>Normal Power</u>	<u>Zero Power</u>	<u>High Power</u>	<u>Low Flow</u>
Test section power, kW	380	388	3.5(max)	478	45.5
Heat flux, 10^6 Btu/hr ft ²	1.323	1.352	0.012	1.664	0.159
Total time at power, min	20	243	--	110	110
Water flow rate, gal/min	48.0	48.2	48.2	48.2	4.8
Water velocity, ft/sec	35.0	35.2	35.2	35.2	3.5
Inlet water temperature, °F	80	85	85	85	97
Outlet water temperature, °F	134	140	85	153	166
Pressure drop, psi	8.5	8.55	11.4	8.3	0.15
Outlet pressure, psia	158	161	161	159	165
Boiling point at outlet, °F	363	364	364	363	366
Average measured outer wall temperature, °F*	470	480	--	547	295
ΔT across wall (calculated), °F	164	168	--	202	21
Average inner wall temperature, °F	306	312	--	345	274
Average bulk water temperature, °F	107	112	--	119	131
ΔT across water film and any scale, °F	199	200	--	226	143
Heat transfer coefficient, Btu/hr ft ² °F	6650	6750	--	7350	1110

* These values are averages of the readings of the 12 reliable thermocouples. They thus indicate temperatures at the center of the test section. The temperatures were also averaged over the duration of the test; those for the Normal Power Test are those at the end of the 20-min cycles.

FIGURE 2. Variation of Surface Temperature with Time

TABLE II. Water Analyses

When sample taken	Well ^(a)	Tank ^(b)	Normal Power Test					High Power Test	Low Flow Test	End of Tests
			Before Start	At Start	During	During	At End			
Sample Designation	J-13	189D	22AB	22CD	27	33	39	41	44	47
pH	7.5	8.1	8.1	8.2	8.3	8.28	8.3	8.25	8.15	8.25
Conductivity, micromhos/cm	280	270	270	270	270	270	270	260	260	260
Total solids, ppm	221	731	225	216	214	225	217	218	205	226
Total solids, after filtration, ppm	206	216	218	215	202	146	215	233	220	210
Hardness, as CaCO ₃ , ppm	36	36	35	35	36	35	36	36	36	36
HCO ₃ , ppm	70	66	63	65	67	67	67	70	68	68
SO ₄ , ppm	12.5	12.5	13.5	14.0	13.0	13.5	13.2	13.5	19.5	13.5
Cl ppm	5.3	6.1	5.6	5.6	5.2	4.5	5.2	5.7	6.2	6.1
F ppm	3.1	3.1	2.3	2.3	3.0	3.2	3.1	3.0	3.0	3.0
NO ₃ ppm	4	8	1	3	1	5	3	4	8	6
Ca ppm	12.9	12.8	12.9	13.1	12.9	12.8	12.7	12.6	12.7	12.7
Mg ppm	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Na ppm	45.5	44.6	44.4	44.0	44.2	44.2	44.1	43.3	43.7	43.8
K ppm	6.2	6.0	5.6	5.7	5.8	5.8	5.8	5.5	5.6	5.6
Fe ppm	0.02	0.04	0.01	0.05	0.01	0.02	0.02	0.06	0.03	0.03
SiO ₂ ppm	67	65	65	68	68	65	67	67	65	71

(a) Sample from well when tank truck filled

(b) Sample from head tank when it was first filled from truck

TEST RESULTS

Only slight changes in surface temperature were observed during the course of the tests, indicating that little or no scale build-up occurred. The variation of surface temperature with time is shown in Figure 2 for the tests at normal and high heat flux. The temperature plotted in Figure 2 is the average of the outside wall temperatures as measured by the 12 reliable thermocouples. These measured temperatures were corrected for the variation due to small changes in inlet water temperature and heat flux from their average values shown in Table I. This correction was at most 4 °F. The temperatures plotted for the normal power test are those at the ends of each of the 20-min cycles.

In the test at normal power, the rise in surface temperature was 4 °F from start to finish of the test. In the test at high power, the surface temperature varied over a total range of 6 °F, but showed a slight tendency to decrease rather than increase with time. In the test at low power and low flow (not shown in Figure 2), there was essentially no change in surface temperature with time, except that caused by variation of the inlet water temperature. The absence of scale build-up during operation at low flow and low power was confirmed by the fact that the surface temperature during operation at a heat flux of 1,644,000 Btu/hr ft² was the same immediately before and after the low flow test.

In addition to the general rise in surface temperature from start to finish of the normal power test, shown in Figure 2, there was a general tendency for the temperature to rise during each cycle of this test. The average rise was 3 °F in each 20-min cycle, again corrected for the effect of any changes of inlet temperature or heat flux. A slight deposit may build up during each cycle and be removed by thermal shock on cooling and reheating. This behavior was not encountered, however, during the longer cycles of the high power test.

The magnitude of the temperature changes observed is only slightly greater than the estimated accuracy of measuring changes in inlet and surface temperatures and heat flux. Therefore, little or no scale build-up occurred.

The test section was cut open at the end of the test and examined for scale deposits. None was found except for a small area near the upstream end of the heated portion, a well-defined band of a brown deposit completely covering the surface in the interval between $5/8$ in. and $1\frac{1}{2}$ in. from the start of the heated length. No thermocouple was located in this region. This deposit was smooth and uniform in texture and could be removed by wiping.

The rest of the inside surface of the test section was covered by a light uniform adherent oxide, characteristic of stainless steel. On part of the surface, this oxide had a pale yellow color which could not be removed by wiping and which may have resulted from inclusion of traces of the brown scale in the oxide as it formed on the heated surface. This color was particularly deep (dark yellow to brown) in the region an inch or so downstream from the brown deposit.

The brown deposit was carefully scraped off the surface and weighed. Its average weight was found to be 0.07 mg/cm^2 . A chemical analysis of the deposit was made by emission spectroscopy, which revealed iron, nickel, and chromium as the principal metallic elements. This indicates that the deposit consisted predominantly of stainless steel corrosion products.

The measured heat transfer coefficient for each of the three tests is shown in Figure 3 as a function of local bulk water temperature. Each point in Figure 3 represents the average of data from two thermocouples; data were also averaged over the duration of each test. In calculating these local coefficients, the heat flux was first calculated as a function of axial position, taking into account the variation of wall thickness and of electrical resistivity of the stainless steel as a function of temperature. The local temperature drop across the wall was calculated for the power generation rate, wall thickness, and thermal conductivity at that point. The local bulk water temperature was calculated by a heat balance. The temperature drop across the water film and scale, if any, was then calculated and used to calculate the heat transfer coefficient.

FIGURE 3. Measured Heat Transfer Coefficients

In the test at low flow and low heat flux, the heat transfer coefficient increased with increasing bulk water temperature, as would be expected because of reduced viscosity. There was a smaller temperature dependence in the high heat flux test, and none in the test at normal heat flux, although it may have been masked by the scatter of the data.

As seen in Figure 3, there was a considerable scatter of the measured heat transfer coefficient from one thermocouple to another, particularly at the higher heat fluxes. Each thermocouple tended to read consistently higher or lower than what would be expected from the readings of its neighbors. However, at elevated temperature (300 °F) with no heat generation all thermocouples agreed very well. Since this discrepancy was present during the operation with deionized water and at the start of the test with well water, it was not due to random scale deposits. We believe that it resulted from perturbation of the local wall thickness and hence, of the local heat generation and temperature drop through the wall, due to welding the thermocouple sheath to the wall. If so, the temperature drop across the wall and the water-film heat transfer coefficient were actually higher than those shown in Figure 3. It would have been preferable in a test of this type to separate the thermocouple sheath from the tubing with a thin layer of electrical insulation, rather than weld it.

The pressure drop across the heated portion of the test section remained essentially constant (within 1%) during each test, again indicating lack of scale build-up. However, the pressure drop decreased significantly with increasing heat flux, as would be expected with a higher temperature and lower viscosity near the surface. This variation with heat flux is shown in Figure 4.

The entire inside heated surface of the tube was examined for corrosion under a microscope at 160X magnification and also subjected to a fluorescent dye penetrant test. No evidence of corrosion was found by either examination.

FIGURE 4. Dependence of Pressure Drop on Heat Flux

DISCUSSION

Since these tests were conducted to determine what behavior would occur in the ETS-1 with untreated water, it is necessary to consider how well the test conditions matched those expected in the ETS-1.

Probably the most significant condition which could not be duplicated in these tests is what happens between the periods at high heat flux. In the ETS-1, a short period of operation at full heat load (5-20 min.) will be followed by a larger tail-off period in which the heat load is much reduced, in the latter portion of which the flow will also be reduced. The exhaust duct cooling system will then be drained and left dry for a period of weeks or months before the next test. This waiting period could result in an aging of any deposit present, which might make it less easily removed by thermal shock or subsequent heat-up. At worst, this might mean that the slight amount of film which appeared to build up during each cycle, instead of being removed between cycles, would be cumulative. If the observed rate of 3°F in 20 min were to remain constant over 3 hr (the estimated total time at full heat load), the temperature rise would be only 27°F . Actually, the rate of build-up appeared to fall off with time in the normal power test, and no build-up was observed in 1 hr at constant power in the high power test. Therefore, aging of the scale between tests in the ETS-1 would produce no more than a small temperature rise.

The ETS-1 exhaust duct will be subject to strong vibrations during use, which were not present in these tests. It seems most likely that if vibration has any effect it would be to reduce scale deposit (in a manner similar to the effect of increased velocity) or to promote scale removal. It is possible, however, that vibration could act through some mechanism to increase scale build-up.

The tubing used in the elbow section of the ETS-1 exhaust duct, where the maximum heat flux and surface temperatures will be encountered, is curved, whereas that in the electrically heated test section was straight. However, the curvature is slight, the radius of

curvature being 350 times the radius of the tubing. Furthermore, an analysis of the flow pattern and heat transfer in curved tubes¹ shows that curvature produces a secondary flow pattern normal to the axis of the tube. This should tend to increase local velocities, improve heat transfer, and reduce scale deposition of all points on the circumference.

The use of Type 321 stainless steel in the test section, rather than Type 347 used in the exhaust duct, should have no effect on scale deposition. The two alloys are virtually identical in chemical composition.

The test was run at the highest heat flux expected in any point in the ETS-1 exhaust duct. At all other points, the heat flux and surface temperature will be less, and therefore, the tendency for scale deposition also less.

The localized deposition encountered near the upstream end was apparently related to an abrupt transition from zero to high heat flux, a condition not encountered in the ETS-1. Thus, the 5/8 in. before the deposit started is interpreted as the distance required to heat the boundary layer and give a high enough surface temperature to cause deposition. In the next short interval of distance, the deposition rate was abnormally high since the water next to the surface was still at bulk concentration with respect to dissolved scale-forming minerals. This surface layer was then depleted as the concentration near the surface approached the solubility of the scale at the surface temperature. The rate of deposition then fell off to a much lower value, controlled by the rate of mass transfer through the surface boundary layer. This smaller amount of scale probably was subsequently redissolved or washed off, leaving a visible deposit at the end of the test only where the deposition had been heaviest.

Even if a deposit comparable in thickness to that observed at the upstream end of the test section were to be encountered in the ETS-1,

¹ Y. Mori and W. Nakayama. "Study of Forced Convective Heat Transfer in Pipes," Int. J. Heat Mass Transfer, vol. 10, pp. 681-695. 1967.

the temperature drop across it would be negligible. If we assume values of 0.5 Btu/hr ft °F and 2 g/cm^3 for the thermal conductivity and density of the scale, respectively, the temperature drop across 0.07 mg/cm^2 of scale would be only 3 °F at a heat flux of $1.35 \times 10^6 \text{ Btu/hr ft}^2$.

We conclude from the results of these tests that there is a very high probability that little or no increase of surface temperature due to scale deposition will occur if untreated Jackass Flats well water is used as a coolant in the ETS-1 exhaust duct, provided that the heat flux, surface temperature, and total time of operation are not greater, nor the velocity less, than in these tests.

The absence of corrosion in this test, however, should not be taken as proof that corrosion will not occur if well water is used in cooling the ETS-1 exhaust duct. The square coolant channels in the exhaust duct contain heated crevices in which high surface temperatures and concentration of impurities by boiling can occur. Therefore, these are more likely places for chloride stress corrosion and other forms of attack than are the tubular channels, in spite of the lower heat flux in the square channels. Furthermore, the heated test section used in these tests had a much smaller temperature difference across the wall, and thus a lower thermal stress on the inner surface than the tubular coolant channels in the ETS-1 exhaust duct. A detailed evaluation of the corrosion problems which might be encountered by using untreated water in the ETS-1 is beyond the scope of this report.

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