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THE N-REACTOR FUEL TESTING PROGRAM IN THE KER LOOPS

T. W. Evans

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HW-77091
Page 1

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THE N-REACTOR FUEL TESTING PROGRAM IN THE KER LOOPS

By

T. W. Evans

N-REACTOR DEPARTMENT

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HW-77091
Page 2

THE N-REACTOR FUEL TESTING PROGRAM IN THE KER LOOPS

The KER Loop fuel testing program was last discussed about a year ago. (1) The purpose of this report is to review the testing environment, to discuss the testing program and to present the schedule as presently seen.

The Testing Environment

The KER loops are four pressurized water-cooled in-reactor testing loops in which fuel, coolant and corrosion tests are being conducted for the N Reactor program. Two of the loops, KER-3 and KER-4, are equipped with N-size Zr-2 process tubes and have sufficient pumping and heat dissipation capacity to permit testing of 14-element charges of N fuel. The other two loops, KER-1 and KER-2, are fitted with Zr-2 process tubes of 2.1" inner diameter (vs 2.7" for N). The small loops can be used to test charges of N inner tubes or other elements sized at about 1.8" outer diameter or less. An inert sleeve must be used with N inner tubes to assure adequate coolant flow over both surfaces of the elements. The KE reactor active zone is 28' long compared to 35' for N so the length of test charges is somewhat shorter than actual N charges will be.

Values of the specific power attainable and expected for several cases of interest are given in Table I. It will be seen that N assemblies in the loops operate at power levels up to 95% of the peak value expected in a 4.4 MW tube in N. Inner tubes alone in the small loops operate at about 170-200% of the peak power expected for an inner tube in N. The KSE3 was a 1.6% enriched single tube element used in a series of tests several years ago. The KSE5 element is similar to the KSE3 but with a slightly greater wall thickness.

TABLE I

PEAK SPECIFIC POWER VALUES FOR N REACTOR AND THE KER LOOPS

<u>Case</u>	(Units-MW/T)		
	<u>Ave*</u>	<u>Outer</u>	<u>Inner</u>
N-5000 KW Tube	18	20	15
N-4400 KW Tube	16	18	13
KER-1, 2**	22	--	22***
KER-3, 4**	15	17	12
KSE3 in KER-1, 2	28	--	--
KSE5 in KER-1, 2	30(est.)		

*Average of the two components of the peak element.

**Winter values.

***The current value is 26.

(1) HW-72680, "KER Loop Fuel Testing Program and Schedule - CY-1962",
T. W. Evans and W. K. Kratzer, February 14, 1962 (CONFIDENTIAL)

DECLASSIFIED

HW-77091
Page 3

It will be seen that the loops provide a good testing environment for first load N-fuel assemblies but with no opportunity for over-power testing. With inner tubes alone or with enriched special elements, we can test at significantly higher power levels than are expected in N. There are, however, two ways in which the loop environment differs significantly from that expected in N. The N reactor cannot be operated with cold water whereas the loops are put on single pass (cold water) cooling whenever pump trouble, leaks or other problems develop. Uranium tends to crack to a much greater degree at the lower metal temperatures associated with cold water cooling. Thus, a test is felt to be seriously compromised whenever it is subjected to this treatment at exposure levels greater than about 500 MWD/T. The second non-prototypic aspect of the KER loop environment pertains to the mode of shutdown in the event of a failure. The reactor is scrammed and the loop water is cooled to room temperature in a matter of five minutes or less. In N, the water temperature will be reduced over a period one to two hours during and after reactor shutdown. Thus, the appearance of a failed element in the loops cannot be taken as typical of what we would expect in N reactor. While the KER loops are not a place where failure testing is done, failures have occurred occasionally. It must be borne in mind that the loops are shut down and cooled off very quickly compared to N reactor and the appearance of failures should, generally, be misleading in the direction of making things look better than they are.

In summary, KER loops #3 and 4 provide a good approximation to N fuel environmental conditions except for the two non-routine situations mentioned above. Loops 1 and 2, although under-size, provide high power, hot water testing conditions for N inner tubes or special test elements.

Testing Program

The KER loop testing program is not an independent activity in and of itself. Loop testing is one phase of the orderly development of several of the metallurgy and reactor programs in progress. Therefore the testing program has its roots in these other programs. The major program breakdowns are described below and those aspects of each for which irradiation testing is required are discussed briefly.

A. Current Fuel Development

The goal of this program is to expand the technology of coextruded Zr-2 clad uranium fuel in order to attain the full capability of this fuel concept at much reduced costs. The testing activities that stem from this program are as follows:

1. Pre-Startup Evaluation of N Fuel

Manufacture of the first load of fuel for N reactor is well underway. Charging is scheduled for early in CY-64, reactor startup is scheduled for late in CY-64, and full power is expected to be reached about one year after startup or late in CY-65. To the extent that the limited KER loop testing capability will permit, the behavior of the N element will be determined by repetitive testing in the full-size loops. Maintenance of this effort through CY-64 and into CY-65 will permit early determination of reactor operational limits imposed by the fuel performance and will provide a basis for program direction during this period.

DECLASSIFIED

HW-77091
Page 4

2. Evaluation of Fuel with Thin Cladding

The thickness of the cladding on the current fuel element was determined somewhat arbitrarily and is believed to be conservative. Since the cost of Zr-2 is a substantial part of the total fuel fabrication cost, use of thinner cladding may result in significant savings. The problem has two facets, broadly speaking. Fabrication development work will be required to determine how cladding uniformity and fuel yield vary as the clad thickness is decreased. Irradiation testing will be required to determine how thin and how uniform the cladding must be to withstand the service conditions imposed on the fuel.

3. Evaluation of a New End Closure Geometry

Although the present end closure appears to be working well there are technical reasons for believing that minor changes in the shape of the fuel-endcap mating surface may reduce the magnitude of the cladding strain that results from the thermal incompatibility of uranium and zirconium and thereby reduce the probability of failure from this cause.

B. Advanced Fuel Development

It has been shown that savings in fuel costs may result from use of a single tube fuel element in place of the tube-tube element now in use. Reduced Zr-2 costs and process simplification are the sources of the savings. Maximum fuel temperatures in the single tube element are 125-150°C higher than in the two piece element so the major technical problem is expected to be swelling. If the amount of swelling is large enough to require thicker cladding then much of the cost reduction potential may be lost. Tests designed to provide swelling information at these higher temperatures are required. Meanwhile, on the presumption that the amount of swelling will be large, work on uranium alloys offering improved swelling resistance has started and study of alternate fuel surface shapes is in progress.

C. Multiproduct Development for N Reactor

The initial attempt to develop processes for making products other than plutonium in N reactor will be centered on tritium production. The lithium-aluminum alloy system is well established as a suitable target material for tritium production in low temperature reactors, but it is unevaluated in the temperature range of N reactor. The technical uncertainties that need to be resolved pertain to diffusion of helium, tritium, and lithium in the target alloy and cladding. KER loop testing will be centered on irradiation of prototype target rods under prototypic conditions to a range of exposure levels spanning and significantly exceeding the range being considered for the N reactor process.

D. Reactor Chemistry Studies

As part of a broad program aimed at developing and expanding the water technology pertinent to the N reactor plant, KER loop #1 was equipped with carbon steel ex-reactor piping (instead of stainless steel as in the other loops). For some aspects of the water chemistry program, in-reactor testing is required and KER-1 is utilized for this purpose. Specific items for which loop testing is required are, in order of priority, (1) evaluation of ammonia

DECLASSIFIED

HW-77091

Page 5

as a substitute for lithium hydroxide for pH control, (2) simulation of an N reactor post-decontamination startup with a thermocoupled fuel element as a crud monitor, and (3) determination of the crud deposition rate at lower pH values than 10.

E. Development of a Crud Monitor for N Reactor

It is deemed desirable to have several crud monitors in N reactor at all times during the first year or two of operation in order to detect whether crud deposition has occurred as a result of the water quality transients which are characteristic of a reactor startup. The crud monitor must generate heat and radiation at levels nearly as great as expected for the fuel in order that fuel fouling be detectable by the crud monitor. Design development tests have been in progress for some time now and will continue until demonstration of a satisfactory design has been accomplished. Proof testing of the design will be carried out to the extent deemed fruitful in the time remaining before reactor application.

Test Details

From conception to evaluation, a KER loop test may take several months or several years depending on the complexity of the test, the need for special procurement and fabrication, or one of several other factors. Some tests may serve one program item, some may serve several. For these reasons, individual tests in progress or being prepared will be described and discussed at this point.

A. Pre-Startup Evaluation Tests

The main purpose in modifying the loops (Project CGI 839) was to make available two loops in which tests of actual N elements could be carried out under power and temperature conditions typical of N reactor at full power. Although modification of the two large loops was completed early last year, operational difficulties have prevented their full utilization. One test to goal exposure at N operating conditions has been completed and another is currently at N goal exposure and scheduled to twice goal exposure. The current plans are to continue tests of first-load elements until operation of N reactor has reached the point where continuation would be pointless. This plan is discussed further later in this section.

The fuel elements for these tests are selected and prepared by personnel of N-Fuels Section. Additional measurements and characterization are carried out by Metallurgy Development Operation (HL) personnel. After irradiation the elements are discharged into a tray at the process tube level, avoiding the long drop to the pad and basin floor. They are transferred to the KE view-pit and are subjected to a thorough post-irradiation examination by personnel of Component Testing Operation (IPD) and Metallurgy Development Operation (HL). The elements are all examined for corrosion, crud, support damage and anything else that can be observed by visual examination. Warp, and dimensional measurements are made for comparison with identical measurements made before irradiation. "Weasel" measurements are made to determine relative exposures of individual elements. The fuel volume changes are measured and ultrasonic determination of uranium integrity, bond integrity and cladding thickness is made. In addition, a small number of selected elements are sent to the Radio-metallurgy Laboratory for sectioning and detailed metallographic examination.

DECLASSIFIED

HW-77091

Page 6

The aspects of performance that are of principal interest are the swelling rate, the mechanical response of the cladding to swelling, crud deposition, uranium cracking, warp and corrosion effects.

How long should this testing be continued? This is an important question deserving careful attention. One argument for continuation is that testing of first load elements will permit early determination of serious deficiencies in the N fuel element. Should a serious deficiency exist and be detected in the loop testing effort, then reactor operational actions may be taken in time to avoid or reduce the severity of reactor problems resulting from fuel malperformance. As will be shown in the Appendix, there are statistical limitations to the thoroughness with which this task may be carried out. A second argument is that early determination of fuel design or process deficiencies will permit fuel plant process changes to be made in a timely manner, perhaps avoiding an excessive backlog of deficient fuel. An equally important benefit of the pre-startup evaluation of N fuel is the guidance that will be provided for direction (or re-direction) of the fuel development program. That is, continued good performance of N fuel will support a shift in R&D emphasis from current fuel to advanced fuel. Poor performance, of course, would justify greater short-term emphasis on the cause and cure of the poor performance.

The principal argument in favor of early termination of current fuel testing is that the lead time for completing a significant design or process modification is quite long and, therefore, evaluation of improvements in the fuel must be started early. Another argument for moderately early termination of current fuel tests is based on the statistical situation (see Appendix), namely that successful completion of a few tests will prove that no really serious deficiencies exist, to be sure, but this is a situation of quickly diminishing returns.

There are valid rebuttals for both sides of the argument. One can argue that process and design improvements can be evaluated just as well in the small loops, using inner tubes or elements especially designed for the purpose of the test. Or one can argue that a failure of an N fuel undergoing test may really have been a true non-recurring "sport". If, indeed, operational changes and R&D program changes were then made on the basis that it was not a sport, a serious diversion of funds and time would have been the result. Other arguments and rebuttals and refinements of the above arguments could be discussed but are deemed to be of less importance than those mentioned.

Looking at the planning problem in more detail, the reactor schedule is shown below in Figure 1.

Figure 1 N Reactor Schedule

DECLASSIFIED

HW-77091
Page 7

According to current plans nearly all the first load will have been discharged at goal exposure or less within 1-2 months after full power is reached. Thus, the testing of the current fuel need continue no longer than late in 1965 in any event (short of a serious delay in the reactor schedule). About two and one-half years of testing (five loop-years or sixty loop-months) is in question. Assuming a time-operating-efficiency of 80% and 1400 MWD/T goal exposure, we compute that it takes five months to complete a fuel test to goal exposure. If we did nothing but test N fuel to goal exposure, we could complete twelve tests in the time available. With one test already complete, a total of about 180 fuel elements would be involved. Statistically, 13 tubes is small compared to the 1000-odd in N reactor and 180 elements is equally small compared to the 18,000 required for a reactor load. As will be developed in the Appendix, the degree of improvement in our knowledge of the fuel failure rate increases steadily as the number of elements successfully irradiated increases, but the rate of improvement decreases rapidly.

An attractive, balanced option that is currently regarded as the best plan is one in which the testing of current fuel is continued in one large loop until late in 1965 and in the other until mid-1964, or halfway to the scheduled date for full power operation. This approach recognizes the fact that the advanced fuel design and multiproduct programs have not progressed far enough that other tests could be ready much before mid-64. It is also clearly recognized that plans made now can be changed rather quickly as new facts come available and program needs are repetitively re-analyzed.

If a significant improvement in loop operating efficiency can be made soon, this schedule would permit irradiation of about 110 elements to goal exposure or higher, allowing for two tests to one and one-half and one test to two times goal exposure.

1. Evaluation of Fuel with Thin-Cladding

Fabrication studies of fuel with thin-cladding have proceeded slowly due to the press of short-term plant problems. There are no firm plans yet for irradiation testing in this program area.

2. Evaluation of a New End Closure Geometry

One test of a modified end closure geometry is currently in progress. There are no firm plans for further loop tests. An early production test in N reactor is deemed a more attractive next step in this area.

B. Advanced Fuel Development

Because swelling is regarded as the most serious potential technical problem in the single tube element and because the large loops are committed to current fuel tests, a new element, the KSE5, has been designed for the smaller loops to simulate the full-sized single tube element. With 1.6% enrichment, the uranium temperature distribution will essentially match that expected in the actual single tube element. Enough elements for three tests are currently on hand and the first test has just begun. The goal exposure will be determined by a cladding strain limit estimated conservatively by extrapolation of existing swelling data. A second test may or may not be run, depending on the outcome of the first test.

Uranium alloy studies have not yet progressed to the point where irradiation

DECLASSIFIED

HW-77091

Page 8

testing is required. British claims for significantly improved swelling resistance in uranium containing (nominally) 900 ppm aluminum and 400 ppm iron must be recognized, however. Work is being initiated which will make enriched fuel of this composition in KSE5 geometry ready for testing late in CY-1963.

C. Multiproduct Development

A series of tests of lithium-aluminum alloys of the composition and enrichment of interest have been planned and elements are being fabricated. Hollow target rods clad in aluminum (unbonded) and clad again in Zr-2 (unbonded) are being used as the test elements. The finished rod diameter is 3/4". N inner tube components will be used to heat the loop water to N temperatures. Exposure levels will span and substantially exceed the range currently felt to be of interest for N reactor.

D. Reactor Chemistry Studies

A reactor startup simulation test has recently been completed in KER-1. Testing of ammonia as a pH control additive is underway and further tests are planned for the near future. Work on a new thermocoupled element is in progress and is expected to be ready within three months. The post-decontamination startup simulation test and a pH variation test will be carried out when the thermocoupled element is ready.

E. N Reactor Crud Monitor Development

Inability to procure good quality Zr-2 sheathed thermocouples has forced reconsideration of the design of the crud monitor element. Ex-reactor tests of mechanical seals are in progress. If they are found to be dependable, use of stainless steel sheathed thermocouples, which are readily available commercially, will be possible. Evaluation of a design using a heavy-walled Zr-2 thermocouple "well" and a stainless steel sheathed thermocouple is in progress. Efforts to obtain Zr-2 sheathed thermocouples are continuing also. No firm plans for the next irradiation test have been made.

Testing Schedule

The schedule, as currently viewed, is shown in Figure 2. KE reactor is in the process of being re-tubed with Zr-2 process tubes. The reactor will be shut down 2-3 times during 1963 for 1-3 weeks each for work on the retubing project.

T. W. Evans

T. W. Evans
Chemistry and Metallurgy Subsection
Research and Engineering Section
N-REACTOR DEPARTMENT

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DECLASSIFIED

HW-77091
Page 10

APPENDIX

STATISTICAL SIGNIFICANCE OF KER LOOP TESTS

KER loop test results to date have offered no opportunity for statistical treatment since there has been no repetitive testing of elements fabricated in a uniform manner. The current plans for repetitive testing of first load elements in KER-3 and KER-4 do introduce the beginnings of a statistical situation. It seemed appropriate, therefore, to discuss some aspects of the statistical significance of the KER loop test results and their relation to N fuel statistics.

The statistic of most interest, of course, is the fuel failure rate. It is clear, intuitively, that the irradiation of 100-odd elements in the loops cannot determine with any great precision what the behavior of tens of thousands in N reactor will be. It is appropriate, however, to ask what level of statistical precision is attainable. The analysis to follow was suggested by Stewart. ⁽¹⁾

After reactor operation is established, the failure rate on a tube basis will be of interest. At the present time, the failure rate on an element basis is more interesting but since each element in a tube experiences different set of temperature and exposure conditions recourse must be made to use of a defined "average" element. The same is true for closures. The assumption is made that the elements tested are representative of the total first load. This is an important assumption, the validity of which is not known.

The question of interest at this point in time is this: Given that some small number of fuel elements (n) have survived irradiation to goal exposure under the anticipated reactor conditions, what can we say about the probability of success of the first load? A solution may be obtained as follows:

If: p = the probability that a unit of production (e.g. an element, a closure or a tube of elements) will complete its service life successfully,

Then: p^n = the probability that n units of production will complete their service life successfully (i.e. with no failures occurring).

In the testing program, we will be increasing n continually and will want to know what has been proven about the value of p for the first load. For the 95% confidence level*, equating p^n to 0.05 will give the minimum value of p for a given n. That is, we have irradiated 14 N elements to goal exposure to date, so, if

$$p^{14} = 0.05$$

Then: $p = 0.81$

Thus, at the 95% confidence level, the failure rate per element is 19% or less. This is more readily seen to be true if one considers the case in which p is

(1) K. B. Stewart, Applied Mathematics Operation (HL)

*This is not the meaning of confidence level used by many statisticians. For lack of a more descriptive term, it will be used here, nevertheless.

DECLASSIFIED

HW-77091
Page 11

exactly 0.81. Then the statement

$$0.81^{14} = 0.05$$

means that there is only one chance in twenty that fourteen successful tests could be completed without failure.

Equating p^n to 0.5, 0.1, 0.01, etc., would give the minimum value of p for the confidence levels 50%, 90%, 99%, etc. In Figure 2, p is plotted against n for several confidence levels.

The curves are replotted in Figure 3 with an amplified vertical scale to relieve the bunching of the curves in Figure 2. It will be seen that, at the 95% confidence level, p is greater than 0.81 for 14 elements. If 100 elements are tested without failure, p then becomes established as greater than 0.97.

Stewart has also suggested an analysis for the case in which one failure has occurred. The probability of getting zero or one defective production unit in a series of tests involving n production units is given by the first two terms of the binomial distribution:

$$p^n + n [p^{n-1} (1-p)] = K$$

The first term is the probability of having zero failures. The expression in brackets gives the probability of a given sequence containing one failure and $n-1$ successes, and the n (outside the brackets) is the number of possible sequences. Taking K as 0.05, again, provides the minimum value of p for 95% confidence, as defined before.

For n greater than 50, use of the Poisson distribution in place of the binomial provides an accurate approximation and makes solution easy. The lower curve in Figure 4 was constructed using the Poisson approximation for $n \geq 50$ plus values determined by convergent iteration at several points for $n < 50$.

Thus, in the testing program for KER-3 and KER-4, every time a test is completed without a failure the lower limit for p is raised as we move up the "no failure" curve in Figure 4. Should a failure occur we would drop down to the "one failure" curve.

In order to complete the interpretation we need to consider what values of p might represent the difference between successful performance of the N fuel and unsuccessful performance. The reactor has about 1000 tubes and a 35 foot active zone so a fuel load will consist of about 18,000 elements, assuming use of two foot elements only. If f is the number of failures that we can stand, then:

$$p \geq \frac{18000-f}{18000}$$

Several values of p as a function of f are tabulated on the next page.

DECLASSIFIED

HW-77091
Page 12

<u>f</u>	<u>P</u>
0	1.00000
1	.99994
2	.99988
3	.99983
10	.99944
100	.99444
1000	.94444

Comparison of the values of p corresponding to three or less failures with the values of p that can be reached by testing several hundred elements successfully gives an indication of the problem. During the next two years we may move up the curve from 0.81 (for 14 elements) to the range 0.97 for 100-150 elements but the curve is bending over sharply and the values of n required for values of p greater than 0.999 is well over 1000. The value of p increases rapidly while n is increasing to the range 100-200 but the improvement slows rapidly beyond here.

FIGURE 2

p Versus n for Several Confidence Levels
(No Failures)

FIGURE 3

p Versus n for Several Confidence Levels, Vertical Scale Amplified
(No Failures)

FIGURE 4

Zero Failure Case Compared with One Failure Case
(95% Confidence Level)

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