Interim Report on the Creepdown of Zircaloy Fuel Cladding

D. O. Hobson
C. V. Dodd

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INTERIM REPORT ON THE CREEPDOWN OF ZIRCALOY FUEL CLADDING

D. O. Hobson C. V. Dodd

ABSTRACT

This report describes the creepdown phenomenon in Zircaloy fuel cladding and the methods by which it will be measured and analyzed. Instrumentation for monitoring radial deformation in the cladding is described in detail in terms of theory, design, and stability. The programs that control the microcomputer are listed, both to document the level of sophistication of the instrumentation and to indicate the reliability of the test equipment.

INTRODUCTION

The creepdown phenomenon, in which Zircaloy fuel cladding deforms under the influence of external pressure and elevated temperature, is of concern to nuclear power reactor designers and operators. Such deformation occurs during relatively long periods -- thousands of hours -- of normal and near normal reactor operation and results in a gradual closing of the gas gap between the cladding and the fuel. If a gap should exist between adjacent fuel pellets, it is possible for the cladding to creep down onto the pellets and then collapse into the gap.

This report describes the creepdown phenomenon, the experimental equipment, and the procedures being used to study cladding creepdown, including some of the development work necessary for the successful functioning of the experimental equipment.

THE CREEPDOWN PHENOMENON

Creep in metals is a time-dependent strain phenomenon that depends upon thermally activated atom movements under an applied stress to achieve specimen deformation. Classically, a uniaxial creep test is characterized by an initial period during which the specimen strains at a decreasing rate with time (primary creep). This is followed by a period in which the rate of deformation is relatively constant with time and is at a minimum value (secondary creep). Finally, the creep rate begins to accelerate with time and continues until specimen rupture occurs (tertiary creep).

The above scenario generally applies to a uniaxial tensile test. How does one relate this to the creepdown of a tubular specimen under the influence of external pressure? Two approaches need to be discussed at this point: the experimental and the computational. The first approach will be discussed in detail later. The latter approach, as utilized by Pankaskie¹ and Mohr² for instance, is based on the assumption of a creep rate that is a function of effective stress. Temperature and external pressure are considered constant. Such a stress is, in turn, a function of the tubing geometry. Pankaskie assumes a deformation mode in which the tube retains an oval shape (cos 2 θ form) to the point of collapse. Mohr places no such restriction

1. P. J. Pankaskie, *BUCKLE - Analytical Computer Code for Calculating Creep Buckling of an Initially Oval Tube*, BNWL-1784 (May 1974).

2. C. L. Mohr, *CØVE-I - A Finite Difference Creep Collapse Code for Oval Fuel Pin Cladding Material*, BNWL-1896 (March 1975).

on the actual shape during deformation. The following discussion is based on Mohr's method for evaluating cladding creepdown.

The algorithm used by Mohr in his CQVE-1 computer code involves an incremental solution procedure in which inelastic changes are computed as small changes to the initial elastic stress state. As time or conditions change, the incremental value is computed as a correction to the previous stress state.

The code logic follows this sequence (quoted from ref. 2, to which the equation numbers refer):

1. Read problem input specifications and interpolate material data for the correct temperature.
2. Compute initial elastic deformation and correction for the finite length. The infinite tube calculation is performed using the closed form solution to the differential equation, with the correction for finite length being applied here.
3. Perform detailed elastic stress calculation.
4. Compute effective stress for all nodal points.
5. For the initial time ($t = 0$) print the initial elastic conditions.
6. Compute creep strains for all nodal points based on the effective stress at these points.
7. Using creep strains, compute bending strain profiles for inplane ($M\theta$) and out-of-plane (Mx) bending. Corrections to the bending stress distributions and creep of the neutral surfaces are also computed. Equations (27) and (28) are used for this calculation.
8. Simultaneous solving for the differential Equations (17c) and (19) using the Numerov approximation shown in Equation (20).
9. Correct the computed deflection results for the finite length approximation and combine in Equations (18) and (19b).
10. Compute bending moment corrections to inplane $M\theta$ and out-of-plane Mx for the finite length.
11. Compute stresses.
12. Compute corrections to the stress states for the inelastic stresses.
13. Compute the rigid body motion or net clad creepdown.
14. Print results.
15. Examine the collapse criteria; if tube has exceeded its criteria the solution is terminated. If not, go on to new time step starting with (3).

The crucial step in this whole sequence is step 6, in which the calculated effective stresses at each nodal point are used to calculate the creep strains that take place during a specified time interval. Such a step requires an analytical model for creep behavior in terms of temperature, stress, and any material response characteristics that might be applicable. It is just such information that is unavailable for Zircaloy under the stress state of interest.

EXPERIMENTAL REQUIREMENTS

What experimental studies could supply the information needed to predict cladding creepdown behavior? One answer would be to conduct uniaxial or biaxial creep tests that simulate the various stress states to which a tubing specimen might be subjected under external pressurization. Creep strain rates, and an

analytical model derived from them, could then be used in step 6 of Mohr's program to calculate cladding strains. Unfortunately, there is a difficulty in this approach that causes some apprehension that it will not work. The number of creep tests to produce the required analytical models would be very large. In addition, the relationship between those models and specimen geometry would remain conjectural. That is, a specimen in the process of deformation will undergo a series of cross-sectional shape changes. Each shape will involve different stress states both through the wall and around the circumference. This causes a certain "chicken, egg" situation: The stress state at any point in the specimen is dependent upon the instantaneous specimen geometry, but the specimen geometry is, in turn, dependent upon preceding stress states. In addition, the specimen tends toward a more and more unstable geometry with time, a geometry that would eventually lead to sudden collapse of a hollow specimen.

The present experimental program undertakes another approach to the problem. Instead of attempting to determine creep rates directly in the classical sense discussed earlier, the specimen deformation is monitored on the basis of shape changes. This is being achieved by a set of closely spaced radial probes set against the specimen surface. The positions of the probes are monitored by eddy-current techniques. This results in a record of the radial positions of up to 23 points within a 0.050-m (2-in.) length on the specimen surface. The data can be recorded at the end of any time interval from approximately 20 sec to 24 hr, so that a high density of data can be obtained during periods of rapid deformation and at a slower rate during periods of slow or steady deformation.

Such data provide a record of the radial movements of certain points on the surface of the cladding. This raises a question: to what extent and how precisely can a surface configuration be described from a knowledge of the radial movements of a limited number of points on that surface? The worth of the entire creepdown study depends upon the answer to that question. Certainly the larger the number of points whose positions are known, the better one is able to describe the surface that contains those points. Also, the simpler the surface configuration, the fewer points are required. The answer to the question can probably be derived from statistical treatment of available data, and, indeed, the data are being investigated.

A second question is raised: how does one handle the probe information in order to "know" the shape of the cladding surface? At any given time during a test, the probes will indicate the position of the surface relative to the starting position. Each probe will also have produced a record of its individual movement with time. It will be a simple task to determine the time at which the cladding contacts the "fuel" pellets: some of the probes will stop moving. Also, initial rippling of the cladding surface can be detected by undulating values of various probes. The surface shape can be modeled at any particular time by fitting the data from the probes with spline functions or two-dimensional Fourier analysis. How closely such a fit is to the real cladding shape will depend on the simplicity of the shape or on a fortuitous choice of expansion functions and can only be determined by further experimentation.

EDDY-CURRENT INSTRUMENTATION

Ordinarily, out-of-reactor tests could have been run in a pressure vessel with a large inside diameter large enough to accommodate linear variable differential transformers (to measure radial strain). Such a system would have allowed the requisite continuous monitoring, but could never have been modified for in-reactor use.

Eddy-current measurement techniques, although quite refined theoretically and in standard use in many areas of experimentation, required extensive development work for use in the present creepdown study. Space limitations, especially for the in-reactor study, required an extremely compact deformation-monitoring system. It was decided to concentrate on the eddy-current-radial probe concept and to design

and build an instrument to control and monitor those probes. Following is a description of the theory and operation of the eddy-current instrumentation.

General theory. The study utilizes coils of aluminum ribbon constructed by winding that ribbon into a spiral as shown in Fig. 1A. A high-frequency alternating current is passed through the coil and produces an alternating electromagnetic field (represented by a vector potential A). When the coil is in air, a purely inductive component of the voltage is produced by this field, and a resistive component of the voltage is developed across the coil dc resistance.³

The coil impedance can be calculated from these components. When the coil is brought near a conductor, as shown in Fig. 1B, the alternating electromagnetic field induces eddy currents in the conductor, which in turn modify the field, causing the resistive component of the coil impedance to increase and the reactive component to decrease. With the coil in an impedance bridge, as shown in Fig. 2, a change is produced in the voltage out (V_o) as the impedance of the test coil varies with respect to the reference coil. The reference coil is alone in air, as shown in Fig. 1A, and the test coil is a distance L from the conductor, as shown in Fig. 1B.

Design of coil. Since the voltage out of the bridge depends on the coil impedance, we first performed a study to determine the best coil design. Using previously developed design data,⁴ and considering the sensitivity of coil-to-disk spacing, change in coil dc resistance with temperature, space limitations, change in resistivity of the disk with temperature, required cable length, available electronics, and available construction materials, we chose the coil and operating properties shown in Table I.

3. C. V. Dodd, W. E. Deeds, and J. W. Luquire, *Some Eddy-Current Problems and Their Integral Solutions*, ORNL-4384 (April 1969).

4. J. H. Smith and C. V. Dodd, "Optimization of Eddy-Current Measurements of Coil to Conductor Spacing," *Mater. Eval.* 33(12), 279 (December 1975).

Fig. 1. (A) Coil wound from flat aluminum wire; (B) coil near a conducting disk.

Fig. 2. Approximate electrical circuit for eddy-current bridge.

Table 1. Coil and operating properties

Coil OD	0.213 in. (0.00541 m)
Coil ID	0.055 in. (0.0014 m)
Coil length	0.032 in. (0.00081 m)
Coil turns	24
Wire cross section	0.0027 in. thick $\times$ 0.030 in. wide (6.9×10^{-3} m) $\times$ (7.6×10^{-4} m)
Coil dc resistance	0.16 Ω at 25 $^{\circ}$ C (77 $^{\circ}$ F)
Coil inductance	1.44 μ H
Operating frequency	2.0 MHz

High test temperatures precluded the use of lacquer-type insulation on the coil ribbon. Also, the need to wind the coil turns very tightly ruled out the use of glass-type insulation between the turns. The problem was finally solved by use of thin aluminum ribbon insulated by a thin ($\sim 3 \times 10^{-7}$ m) anodized oxide coating. This allows virtually metal-to-metal contact between the turns. The oxide film is quite adequate for insulating against the ~ 15 -V potential across the coil.

The impedance was calculated⁵ for this coil at both room temperature and 427 $^{\circ}$ C (800 $^{\circ}$ F), with various spacings (lift-offs) between the coil and a 0.25-mm (0.010-in.) copper coating on a stainless steel disk.

A plot of these results is shown in Fig. 3. The impedances have been normalized by dividing both components by the magnitude of the reactance of the coil in air (ωL_0).

5. W. A. Simpson, C. V. Dodd, J. W. Luquire, and W. G. Spoeri, *Computer Programs for Some Eddy-Current Problems* 1970, ORNL/TM-3295 (June 1971).

Fig. 3. Normalized impedance for various values of coil-to-conductor spacing (L) at room temperature and 427°C (800°F).

The impedance change is a nonlinear function of the spacing change, and there is very little change in the magnitude of the coil impedance as the temperature varies from 21° to 427°C (70° to 800°F).

Analysis of bridge circuit. These impedance values are put into the bridge circuit, and the voltages for the various values of the bridge parameters can be calculated. The voltage out of the bridge circuit in Fig. 2 is given by

$$V_o = V_i G \left[\frac{Z_{p2}(R_{h1} + R_{x1} + Z_{p1}) + j\omega C_{s1} R_{s1}}{Z_{p1}(R_{h2} + R_{x2} + Z_{p2}) + j\omega C_{s2} R_{s2}} \right] \div \left[(R_{h1} + R_{x1} + Z_{p1})(R_{h2} + R_{x2} + Z_{p2}) + j\omega C_{s1} R_{s1} + j\omega C_{s2} R_{s2} \right] \quad (1)$$

where

$$Z_{p1} =$$

$$\frac{(1 + j\omega C_{s1} R_{s1}) \{ R_{R1} [1 + j\omega C_{CAB1}(R_{C1} + Z_1)] + R_{C1} + Z_1 \}}{(1 + j\omega C_{s1} R_{s1}) [1 + j\omega C_{CAB1}(R_{C1} + Z_1)] + j\omega C_{s1} \{ R_{R1} + [1 + j\omega C_{CAB1}(R_{C1} + Z_1)] + R_{C1} + Z_1 \}} \quad (2)$$

and Z_{p2} has an identical form with subscript 2 in place of subscript 1. The subscript 1 is used for the reference side of the bridge, and the subscript 2 is used for the test coils (which are switched in at different times). The variable resistances R_L and R_R are used to adjust the reactive and resistive components of the bridge respectively. The resistance R_{c1} is the cable and coil resistance, and this varies with temperature. Although the cable capacitance, C_{CAB1} , is shown as being connected between R_R and R_{c1} , it is actually distributed along part of R_{c1} . The switch resistance and capacitance are shown as R_s and C_s , and the differential amplifier gain is G . While this circuit is a simplified approximation of the actual circuit, it is a very good approximation and represents the major effects. The nominal values of the bridge parameters are given in Table 2. While most of the bridge components are quite stable, some of them do vary and cause errors in the measurements.

The errors in the coil-to-conductor spacing measurement due to drifts in the circuit are summarized in Table 3. Since the impedance change is a nonlinear function of the coil-to-conductor spacing, the amount of error in some instances will change with the amount of spacing. The major errors are due to the variation in other components of the system, namely, in the copper resistivity (1.732 to 3.03 $\mu\Omega\text{-cm}$) and the dc resistance change (2.7 to 3.0 Ω) as the assembly is heated. Also, a change in the cable capacitance that is not balanced by a similar change in the other leg of the bridge can cause a large error. The operating frequency is about one-tenth the resonant frequency and will have to be reduced if the capacitance is increased by any large amount. In general, however, the errors are quite small. The input voltage, V_{in} , is also used for the reference voltage, so variations in this voltage produce no errors. There is a digitizing error

Table 2. Nominal values of bridge parameters

Parameter	Value	Units
V_i	10	Volts, p-p
R_{b1}, R_{b2}	150	Ohms
R_{x1}, R_{x2}	0-50	Ohms
R_{s1}, R_{s2}	65	Ohms
C_{s1}, C_{s2}	100	Picofarads
R_{R1}, R_{R2}	0-5	Ohms
R_{c1}, R_{c2}	3	Ohms
C_{CAB1}, C_{CAB2}	830	Picofarads
G	15	
Z_1	$0 + j17$	Ohms
Z_2	$0.15 + j15$	Ohms
Frequency	2×10^6	Hertz

Table 3. Summary of errors (nads) due to drifts in various circuit parameters

Parameter varied	ρ and R_{c1}	R_{c1}	R_{s1}	C_{s1}	C_{CAB1}	C_{CAB1}, C_{CAB2}	A/D
Nominal value	3.08-3.00 Ω	3.00 Ω	65.0	100 pF	830 pF	830 pF-850 pF	Digitizing
New value	1.73-2.7 Ω	3.03 Ω	65.1	110 pF	838 pF	838 pF-838 pF	error
Error at							
0.010 in. (2.54×10^{-4} m)	0.90	+0.04	+0.004	+0.11	0.130	0.097	+0.008
0.020 in. (5.08×10^{-4} m)	0.91	+0.04	+0.006	+0.11	0.188	0.106	+0.012
0.030 in. (7.62×10^{-4} m)	0.90	+0.05	+0.008	+0.12	0.266	0.112	+0.016
0.040 in. (10.16×10^{-4} m)	0.90	+0.05	+0.011	+0.10	0.365	0.116	+0.023
0.050 in. (12.7×10^{-4} m)	0.90	+0.05	+0.014	+0.08	0.490	0.118	+0.030

in the analog-to-digital converter which will also produce a small error, as shown in Table 3. The voltage readings can be converted to lift-off values to within $\pm 3.81 \times 10^{-6}$ m (0.00015 in.), using a simple polynomial in the natural log of the voltage, according to the equation

$$\text{spacing} = C_0 + C_1 (\ln V) + C_2 (\ln V)^2 \quad (3)$$

This equation is determined during the calibration process for each coil.

Now that we have discussed the design of the bridge circuit for making the measurements, we will discuss the overall instrumentation used.

Computer system to measure spacing for an array of coils. Since we need to measure the spacing for an array of coils, we designed a computer-controlled instrument, shown in Fig. 4, to perform the measurements, linearize the results, compute the changes in dimensions, and stop the test when the changes reach a preset level. The power amplifier is used to generate a 10-V (peak to peak) signal, which is applied through a resistance to all 24 coils. Each resistor and coil forms one side of the bridge shown in Fig. 2, and the reference coil forms the other side. The bridge is formed when the signal from one of the 23 test coils is switched into the differential amplifier to be compared with the signal from the reference coil (which remains switched on). The difference signal is amplified, and its magnitude is converted to dc. This analog voltage is converted to a digital signal with a 13-bit, analog-to-digital converter. The digital signal is fed into a microcomputer, where the signal is processed in various ways and then sent to both serial and parallel data storage devices. In addition, the computer is used to control the CMOS switches on the coils, generate the timing signals for the analog-to-digital converter, and respond to the various front panel switches and a preset clock. The microcomputer, an NDT-COMP8, was developed for general eddy-current tests and is covered in a separate report.⁶ The microcomputer is used to control both the actual tests and the calibration and setup of those tests.

Operation of the microcomputer-controlled creepdown instrument. The creepdown instrument is operated by the controls shown in the upper left-hand corner of Fig. 5. When the RESET push button is activated, it resets the computer and puts all of the input-output lines in the high-impedance state. The computer will respond to data from a terminal device in this state through the NDT-COMP8 monitor programs. The START button initiates the execution of the main control program. The terminal is then used as an output-only device.

The STROBE button will cause data to be printed on both the terminal and the thermal printer (if they are on line). If the system is in the RUN mode, a STROBE signal will cause all 23 channels to be read and printed out. This signal is obtained from either the front panel push button or the preset clock. The clock will then reset itself and start the timing cycle again.

If there is no strobe signal, the computer will SCAN all 23 channels, making a single reading of each channel. If the MILS switch is on and the lift-off has been zeroed at least once, the value of lift-off of each channel will be compared with preset maxima and minima and halt execution (STOP) if these limits are exceeded. If a STOP occurs, all 23 channels will be printed out, the clock halted, and then the computer stops the program.

If a STROBE signal is received when both the MILS switch and the SET ZERO switch are on, the lift-off and the count number will be zeroed. If the A/D OUTPUT switch is on, the raw analog-to-digital converter readings will be printed out.

6. C. A. Dodd and G. D. Connell, *The NDT-COMP8 Microcomputer*, ORNL/TM-5773 (March 1977).

Fig. 4. Block diagram of computer-controlled eddy-current instrument for measuring creep for an array of coils.

Fig. 5. Controls for the creepdown instrument.

If the system is in the CALIBRATE mode, a STROBE signal will cause either 23 or 24 channels to be read, and the last one will be printed out. The clock will not be reset. If the SINGLE STEP switch is on, the channel printed out will be one greater than the previous one. If the NO STEP switch is on, the same channel that printed out the last time will print out again. If the 23rd channel was printed out the last time, SINGLE STEP will cause the first channel to print out with the next STROBE signal. The value will be printed in mils with the MILS switch on, or the raw analog-to-digital converter value will be given with the A/D OUTPUT switch on.

In the RUN mode, the count number will be printed at the start of each set of readings and a line feed will operate at the end. The channel number of the reading is also printed to the left of each reading. The terminal will print out the exponent of the reading if it is not zero, but the thermal printer ignores the exponent.

When the RUN switch is on, each reading printed out is the average of eight analog-to-digital converter readings. In the CALIBRATE mode, however, only the result of a single reading is printed. Any value of time between 10 sec and 24 hr can be preset into the clock switches, although the readings and printing take about 25 sec (with a 300-baud printer).

Now that we have seen how the instrument operates, we will discuss the computer programs used.

Computer programs for the creepdown test. The instrument uses both read-only memory (ROM) and read-write memory (RAM) for its operation. The ROM is used for program storage, the RAM is used for storage of intermediate results, and both are organized in 1K (1024) by eight segments as shown in Fig. 6. There are three of these segments used for ROM and one for RAM.

ORNL-DWG 77-3545

Fig. 6. Memory map of computer used for creepdown tests.

The addresses in Fig. 6 are given in both decimal and hexadecimal (base 16). For the remainder of this section, only hex addresses will be used. Only the first three ROM and the last RAM sections actually have memory chips plugged into them (the sockets are blank in the others). The discussion of the NDT-COMP8 and the floating-point math package are given in ref. 4 and will not be repeated here. A list and summary of the programs in the memory for the control of the creepdown test are given in Table 4. All of these programs are contained in a single PROM (programmable read-only memory) chip, which is plugged into the address starting at 400 (hex).

In addition to the program storage in ROM, there are 3 bytes X 23 channels stored for the C_{2L} constants (from 45B to 49C) and 3 bytes X 23 channels stored for the C_{1L} constant (from 4A0 to 4D5). In both cases the first byte is the exponent, the second byte the high part, and the third byte the low part of the mantissa. The RAM storage used is summarized in Table 5. A listing of the individual programs is given in the Appendix.

EXPERIMENTAL DESIGN

The original design for the eddy-current coil probe array, which consisted of four sets of axially distributed probes, was tested in two creepdown experiments. The design was found unsatisfactory because of difficulties in calibration due to the lack of individual coil adjustment capabilities. We have redesigned

Table 4. Creepdown program FROM

Name	Address	Program function	Destroys registers
Setup	0400	Program programs Part I $C_4 - 1 C_m$ for output, 1A 1B and 1 $C_0 - 1 C_1$ for input. Parts II and III are programmed for output program checks to see if zero L.O. in RAM is to be zeroed, and starts the clock and goes to the main control program.	A B C D E F I
MANCT	043F	Main control program. Forms a "control word" using the SET ZERO bit and the front panel switch positions. Then calls SCAN, CALIB, RUN, or loops back on itself, depending on the "control word."	A B C D E H L F
AVGDT	053F	ZEROES 46 memory locations in RAM, then calls ADRED for all 23 channels 8 times each and stores the sum of each channel in 2 RAM locations (in fixed binary). Returns to calling program.	A B C D E H L F
CLKST	0580	Resets and restarts the clock, calls TIMER, returns to calling program.	A B
SETLO	059A	Program sets the current lift-off value to zero. Takes a floating number in CDE (the current lift-off value), with the channel no. in L, changes the sign, adds the previous value of zero lift-off in RAM and stores the new value back in RAM. Then the SET ZERO bit is reset to 0, the count number is zeroed, and program returns to the calling program.	A B C D E H L F
LINAR	0538	Program takes a floating point number in CDE with the channel number in L and converts it into mils lift-off using $L.O. = C_{0L} + C_{1L} \ln M_L + C_{2L} (\ln M_L)^2$. C_{1L} and C_{2L} are stored in ROM and C_{0L} is stored in RAM. The program returns the answer in CDE and the channel no. in L.	A B C D E F
STOP	0621	Program calls RUN 1, which prints all 23 channels without resetting the clock, stops the clock, and sends part 1 CS low to stop experiment. Program goes back to NDT-COMP8 monitor and halts.	A B C D E H L F
LMST	062B	Takes a floating-point number in CDE and compares it with an upper and lower limit. Calls STOP if limits are exceeded.	A B C D E H L F
SCAN	064C	Makes a single reading of each channel. Will test it against the limit (call LMST) if the results were linearized (MILS switch on) and the lift-off has been zeroed (SET ZERO bit off). Returns to MANCT when finished.	A B C D E H L F
TIMER	066D	Gives a delay of about 4 msec when called. Returns to calling program.	A B C F
RUN	067A	Resets the clock, increments, and prints the count number. Calls AVGDT. Linearizes the data if MILS switch on, sets zero L.O. if MILS and SET ZERO switches on, prints out data in indicated form. Returns to calling program.	A B C D E H L F
DATRD	06D3	Reads the last AD converter results, linearizes if MILS switch is on, and returns with floating number in CDE.	A B C D E H L F

Table 4 (continued)

Name	Address	Program function	Destroys registers
CALIB	0611	Will call the ADREFD program either 23 times with NO STEP switch on, 24 times with SGL STEP switch on. Will print out result of last reading in MILES if switch on or raw A/D convert readings otherwise. Jumps back to main control program.	A B C D E H L I
ADREFD	0712	Reads the AD converter, increments the channel number, stores the data in memory, and starts the next conversion. The channel number is sent to the proper CMOS switch to switch the proper coil on. Will start channel number back at 1 when 23 is exceeded.	A B C D E H L I
DCML	0761	Takes a binary floating-point number in CDE and converts it into a fixed decimal number in CDE with the exponent and sign in H. The binary channel number in L is converted to a decimal number in L. Returns to calling program with data in C, D, E, H, and L.	A B C D E H L I
TYPTR	0791	Takes a decimal number in CDE, channel no. in L, and exponent in H. Will blank L if it is zero, and exponent if it is zero. Return to calling program.	A
THPTR	07F3	Prints sign in H, channel number in L, and decimal number in DE. Exponent and number in H are not printed. Returns to calling program.	A

Table 5. Summary of RAM storage

Address	Used to store
1C0D	The value of the 1CPORT (from the front panel switches)
1C01-1C02	The count number (the number of "RUN" readings made)
1C03-1C04	Check number, to see if zero L.O. should be set to zero
1C05-1C08	In M_0
1C09	Set zero lift-off status word 1000 0000 if not set, 0000 0000 if set
1C10-1C1F	Used by floating-point math package
1C20	Chno (channel number)
1C22-1C52	AD converter data (2 bytes each for 24 channels)
1C53-1C99	COL (floating value of the zero lift-off, 3 bytes each for 23 channels)
1CA2-1CFF	Average values for 23 channels, 2 bytes per channel
1FBD-1FFF	Reserved for stack

the system to provide a double-helical arrangement of coils mounted in a cylindrical aluminum block that surrounds the specimen tube. The probe orientation is shown in Fig. 7. The probes extend over a 50.8-mm (2-in.) length and are spaced 6.35 mm (0.25 in.) apart. Each coil is individually adjustable in the radial direction and can be balanced and calibrated in situ by means of special mandrels inserted into the aluminum cylinder. The coil and probe arrangement within the cylinder is shown in Fig. 8.

The double-helix configuration, positioned within the aluminum cylinder, is also going to be used in the in-reactor tests in the Netherlands. Our present use will give experience with the test configuration before the in-reactor tests start.

ORNL-DWG 75-21003

Fig. 7. Orientation of eddy-current probes in creepdown test.

ORNL-DWG 77-4106

Fig. 8. Arrangement of coil and probe with respect to cylinder under test.

CONCLUSIONS

This report discusses the mechanics of the creepdown process as applied to Zircaloy fuel cladding. Particular emphasis is given to the differences between the test methods necessary for the study of cladding creepdown due to external pressure and the methods used to study more conventional stress states.

The equipment described herein and the experimentation in which that equipment will be used have been designed and developed for this study. The problems addressed are technically complex and experimentally difficult, as shown by the fact that there is no information available on the continuous creep behavior of a fuel cladding tube subjected to external pressurization. The apparatus described in this report is capable of providing such information and, in addition, is capable of providing it in an in-reactor environment.

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APPENDIX

Table A.1. SETUP - Program to set the ports and start execution

Add	Mac. Lan.	Label	Code Op.	Comments
0400	3F 93	SETUP	MVI A, 93	Load program word into A
	D3 F7		OUT PORT 1P	Send to port 1P (program)
	3F 30		MVI A, 30	Send 0011 0000 to port 1C
	D3 F6		OUT PORT 1C	to set bits, 1C4 for counter, 1C5 for stop.
	3F 80		MVI A, 80	Load program word for all outputs
	D3 EF		OUT PORT 2P	Send to port 2P
	D3 DF		OUT PORT 3P	Send to port 3P
040E	2A 03 1C		LHLD Ck. No.	Load the check no. into HL from RAM.
	11 55 55		LXI D, 5555	Load its complement into DE.
	19		DAD D	Add HL to DE and increment
	11 01 00	LOOP 1	LXI D, 00 01	once answer = 0 with carry set
	19		DAD D	if RAM has not been changed
	DA 3B 04		JC CONT	Jump around if RAM has not been changed
	21 AA AA		LXI H, AAAA	Load new check no. into HL
	22 03 1C		SHLD Ck. No.	and store. RAM values of Co will be
	21 99 1C		LXI H, 1C 99	set to 0. Load max. address of Co in HL
	11 00 00		LXI D, 00 00	Load a floating point 0 in
	0E 40		MVI C, 40	CDE
	06 18		MVI B, 18	Load B counter for 24 channels
042C	73		MOV M, E	Move E, D, & C to memory
	2B	CONT	DCX H	for each of 23 channels
	72		MOV M, D	
	2B		DCX H	
	71		MOV M, C	
	2B		DCX H	
	05		DCR B	Decrement counter
	C2 2C 04		JNZ LOOP 1	Return to LOOP 1 if not complete
	3F 80		MVI A, 80	Load a status bit in zero lift-off
	32 09 1C		STA ZRLOST	status to indicate that lift-off isn't zero
043B	CD 80 05		Call CLKST	the clock started

Table A.2. MANCT - Main control program

Add	Mac. Lan.	Label	Code Op.	Comments
043E	3A 09 1C	MANCT	LDA ZRLOST	Load the zero lift-off byte
	6F		MOV L, A	(1000 0000 if not set, 0 if set) move to L
	DB F6		IN PORT 1C	Port 1C is loaded into A and 1C ₇
0444	B5		ORA L	is set high if L.O. is not zeroed.
	32 00 1C		STA PORT 1C	The results of the port are stored in RAM
	F6 03		ANI 03	Dump all bits except 1C ₆ and 1C ₇
	CA 4C 06		JZ SCAN	If both 1C ₆ and 1C ₇ are zero, jump to SCAN
	0F		RRC	Rotate 1C ₆ into carry
044E	D2 3E 04		JNC MANCT	Loop back if STROBE (1C ₆) is low
	0F		RRC	Rotate 1C ₇ into carry
	DA F1 06	CALIB	JC CALIB	If calibrate (1C ₇) is high, jump to CALIB
	CD 7A 06		Call RUN	No calibrate STROBE means RUN
0458	C3 3E 04		JMP MANCT	Return to start of control program

Table A.3. AVGDT - Averages data (8 values of 16 different channels)

Addr	Max. Len.	Label	Code Op.	Comments
053F	21 A2 1C	AVGDT	LXI H, 1C A2	Load ch. no. address + 2E HEX
	AF		XRA A	Zero A
	0F 17		MVI C, 17	Sets counter in C reg (23 channel)
0545	77	LOOP 1	MOV M, A	Zero all 23 channels
	23		INX H	in RAM (2 bytes per channel)
	77		MOV M, A	
	23		INX H	
	0D		DCR C	
	C2 45 05		JNZ LOOP 1	Jump to LOOP 1
	06 08		MVI B, 08	Load 08 into the B counter (08 values)
054F	0E 17	LOOP 2	MVI C, 17	Load 17 into the C counter (23 channels)
0551	C5	LOOP 3	Push B	Store BC register on stack
	CD 12 07		Call ADRED	STROBE A/D converter
	3A 2D 1C		LDA Ch. No. Addr.	Load the channel no. into A
	3D		DCR A	
0559	C2 5E 05		JNZ CONT 1	Jump to CONT 1
	3E 17		MVI A, 17	Make ch. no. 23 if it was 0 when decreased
055E	4F	CONT 1	MOV C, A	Put ch. no. into C register
	06 00		MVI B, 00	
0561	21 2D 1C		LXI H, Ch. No. Addr.	Load ch. no. address into HL
	09		DAD B	
	09		DAD B	
	5E		MOV F, M	HL contains ch. no. address + 2 x ch. no.
	23		INX H	
	56		MOV D, M	DE contains last A/D reading
	01 80 00		LXI B, 00 80	0080 HEX is loaded into BC
	09		DAD B	HL contains 1C30 + 2 x ch. no. + 1
	46		MOV B, M	Move high order into B
	2B		DCX H	
	4E		MOV C, M	Move low order into C
0570	EB		XCHG	Exchange HL and DE
	09		DAD B	Add HL to BC, sum in HL
	EB		XCHG	1C30 + 2 x ch. no. in HL, sum in DE
	73		MOV M, E	Store low order in memory
	23		INX H	
	72		MOV M, D	Store high sum in 1C30 + 2 x ch. no. + 1
0576	C1		POP B	Restore counters
0577	0D		DCR C	Decrement channel counter
	C2 51 05		JNZ LOOP 3	Loop over channels
	05		DCR B	Decrement no. of readings counter
	C2 4F 05		JNZ LOOP 2	Loop over readings per channel
057F	C9		RET	Return

Table A.4. CLKST - Starts the clock

Add	Max. Len.	Label	Code Op	Comments
0580	3F 20	CLKST	MVI A, 20	Sets reset (IC _g) Set low
	D3 F6		OUT PORT IC	(Stop bit is left high)
	CD 6D 06		Call TIMER	Inverts a time delay
0587	3F 30		MVI A, 30	Sets reset (IC _g) high
	D3 F6		OUT PORT IC	
	CD 6D 06		Call TIMER	Inserts a time delay
	3F 00		MVI A, 00	Sets start (IC _g) bit high
	D3 F6		OUT PORT IC	
	CD 6D 06		Call TIMER	Insert a time delay
0597	3F 30		MVI A, 30	Set start (IC _g) low
	D3 F6		OUT PORT IC	
0599	C9		RET	Return

Table A.5. SETLO - This program takes a floating point number in CDE, ch. no. in L, changes the sign, adds the value to C_{OL}, and replaces the value of C_{OL} in RAM. The status of the zero left-off bit is then changed to 0 (Set)

Add	Max. Len.	Label	Code Op.	Comments
059A	CD F8 08	SETLO	Call FNEG	CDE is changed to - CDE
	D5		Push D	Save on stack
	C5		Push B	
	26 1C		MVI H, 1C	1C 4F starting add 3
	3F 4F		MVI A, 4F	
	85		ADD L	
	85		ADD L	
	85		ADD L	
	6F		MOV L, A	1C 4F + 3 x ch. no. in HL
	4F		MOV C, M	Old value of C _{OL} is moved
	23		INX H	into CDE
	56		MOV D, M	
	23		INX H	
	5E		MOV E, M	
	22 0A 1C		SHLD LH, Adr.	Ch. no. address is stored in RAM
05B0	F1		POP H	- CDE is moved back
	45		MOV B, L	into BHL
	E1		POP H	
	CD 13 08		Call FADD	Add - CDE to previous L.O. value
	2A 0A 1C		LHLD LH, Adr.	Load address of 1C 4F + 3 + ch. no. + 2
	73		MOV M, E	
	2B		DCX H	
	72		MOV M, D	
	2B		DCX H	
	71		MOV M, C	
	AF		XRA A	
	32 01 1C		STA Count No.	Store count no.
	32 02 1C		STA Count No.	
	32 09 1C		STA 1C 09	Store zero L.O. set bit (ZRL0ST)
05C7	C9		RET	Return

Table A.6. LINAR - Takes a floating point no. in CDE, with ch. no. in L, and converts it to a linear function of left-off in CDE, ch. no. in L. L.O. = $C_{0L} + C_{1L} \ln M_L + C_{2L} (\ln M_L)^2$

Add	Mac. Lam.	Label	Code Op.	Comments
05C8	E5	LINAR	Push H	Ch. no. is stored on stack
	26 00		MVI H, 00	H is zeroed
	7D		MOV A, L	Ch. no. is moved to A
	87		ADD A	Ch. no. is doubled
	85		ADD L	and added to itself.
	64		MOV L, A	3 x ch. no. in HL
	E5		Push H	3 x ch. no. is stored on stack
	CD 0D 0A		Call FLN	In M_L is in CDE
	EB		XCHG	
	22 05 1C		SHLD 1C 05	In M_L is stored 1C 05 - 1C 0E
	69		MOV L, C	
	22 07 1C		SHLD 1C 07	
	E1		POP H	3 x ch. no. is restored in HL
	E5		Push H	and retained on stack
	01 4F 1C		LXI B 1C 4F	Zero add for C_{0L}
05ED	09		DAD B	HL are set for C_{0L}
	4E		MOV C, M	
	23		INX H	
	56		MOV D, M	C_0 is loaded in CDE
	23		INX H	(Exponent, hi byte, lo byte)
	5E		MOV E, M	
	E1		POP H	HL is restored (3 x ch. no.)
	D5		Push D	C_0 is stored on the stack
	C5		Push B	
	E5		Push H	3 x ch. no. is retained on stack
05F0	01 9D 04		LXI B 04 9D	Zero add for C_1 is loaded
	09		DAD B	HL contain C_{1L}
	4E		MOV C, M	C_1 is loaded in CDE
	23		INX H	(Exponent, hi byte, lo byte)
	56		MOV D, M	is stored at 049D + 3 x ch. no.)
	23		INX H	
	5E		MOV E, M	
	E1		POP H	
	D5		Push D	C_1 is stored on stack
	C5		Push B	
05F9	01 58 04		LXI B 04 58	Zero add for C_2 is loaded
	09		DAD B	HL contain C_{2L}
05FA	4E		MOV C, M	
	23		INX H	
	56		MOV D, M	C_2 is loaded in CDE
	23		INX H	
0602	5E		MOV E, M	
	2A 07 1C		LHLD 1C 07	In M_L is loaded (exponent in B, mantissa in H, L)
	45		MOV B, L	
	2A 05 1C		LHLD 1C 05	
	C7 7B 09		Call FMPY	C_{2L} in M_L in CDE
	E1		POP H	
	45		MOV B, L	C_1 is restored to BHL
	E1		POP H	from stack
0612	CD 13 08		Call FADD	$C_1 + C_2$ in M_L in CDE
	2A 07 1C		LHLD 1C 07	
	45		MOV B, L	In M_L is loaded in HL
	2A 05 1C		LHLD 1C 05	
	CD 7B 09		Call FMPY	In M_L ($C_1 + C_2$ in M_L) in CDE
	E1		POP H	
	45		MOV B, L	C_0 is restored from stack
	E1		POP H	
0620	CD 13 08		Call FADD	$C_0 + C_1$ in $M_L + C_2$ (in M_L) ² in CDE
	E1		POP H	Ch. no. is restored in L
0620	C9		RET	Return

Table A.7. STOP

Add	Mac. Lan.	Label	Code Op.	Comments
0621	CD 94 06 3E 10	STOP	Call RUN 1	Print out all channels
	D3 16		MVI A, 10	Load (000) (0000) in A
0628	C3 2B 00		OUT PORT 1C	Send to port 1C
			JMP 00 2B	Jump to NDI-COMP 8 MONITOR

Table A.8. LMTST - Takes a floating point number in CDE and tests to see if it exceeds the test bounds.
Calls a RUN if it does, then calls STOP.

Add	Mac. Lan.	Label	Code Op.	Comments
062B	C5 D5	LMTST	Push B	Save CDE on stack
	21 00 A0		Push D	
06 45			LXI H, A000	Upper limit (20.00 mls) loaded into BHL
CD 10 08			MVI B, 45	
79			Call FSUB	A floating point subtract is performed, answer in CDE
F6 80			MOV A, C	
C4 21 06			ANI 80	Sign bit in C is tested
D1			CNZ STOP	Stop subroutine is called if limit exceeded
71			POP D	Limit-off is restored to CDE
	21 00 A0		POP B	
06 C5			LXI H, A0 00	Lower limit (- 20.00 mls) is loaded into BHL
CD 10 08			MVI B, C5	
79			Call FSUB	A floating point subtract is performed
F6 80			MOV A, C	Sign bit of answer is tested.
CC 21 06			CZ STOP	STOP subroutine is called if answer is +
064B	C9		RET	Return

Table A.9. SCAN - Makes readings and checks limits without printing or advancing count number

Add	Mac. Lan.	Label	Code Op.	Comments
064C	3E 18 32 20 1C 3D	SCAN	MVI A, 18	Set up the channel no. in
F5			STA Ch. No. Adr.	address 1C20, counter in A
CD 12 07		LOOP	DCR A	decrement counter and store on stack.
F1			Push PSW	
CD 12 07			Call ADRED	Make an AD conversion
F1			POP PSW	Restore counter from stack
3D			DCR A	and decrement
CA 3E 04			JZ MANCT	Return if finished.
F5			Push PSW	Restore counter to stack
CD 12 07			Call ADRED	Make an AD conversion
CD D3 06			Call DATRD	Reduce the data
3A 00 1C			LDA PORT 1C	Check status of 1C port (at start of SCAN)
F6 84			ANI 84	1000 0100 check IC ₂ bit, IC ₇ bit
71 2B 06			CZ LMTST	if zero, test for out of limit reading.
066A	C3 56 06		JMP LOOP	Loops back

Table A.10. TIMER – Gives a delay of about 4 msec.

Add	Mac. Lan.	Label	Code Op.	Comments
066D	E5	TIMER	Push H	Save H on the stack
	01 A0 00		LXI B, 00 A0	A0 is loaded into B
	21 00 00		LXI H, 00 00	Zero HL
0674	09	SUM 1	DAD B	Add B to HL
	D2 74 06		JNC SUM 1	Jump back if sum is < 65K
	F1		POP H	
0679	C9		RET	Return

Table A.11. RUN – Resets the clock, increments the count no., reads all 23 channels 8 times each, prints each channel, sets the zero lift-off if indicated

Add	Mac. Lan.	Label	Code Op.	Comments
067A	CD 80 05	RUN	Call CLKST	Starts the clock over
	2A 01 1C		LHLD Count No.	The count no. is loaded from memory, incremented and restored into memory; a copy is moved into DE, and converted to decimal.
	23		INX H	No print advance
	22 01 1C		SHLD Count No.	The count no. is printed out on the thermal printer and terminal.
	EB		XCHG	All 23 channels are read, 8 times each
	CD 33 0A	RUN 1	Call Fx BIDECL	23 (decimal) is loaded into A
	21 00 1F		LXI H, 1F 00	Adr. of highest channel with avg. data in HL
	CD E3 07		Call THPTR	
	CD 91 07		Call TYPTR	
	CD 3F 05		Call AVGDT	
0694	3F 17	RUN 2	MVI A 17	
	21 CF 1C		LXI H 1C CF	
0699	56		MOV D, M	
	2B		DCX H	
	5F		MOV E, M	Avg. value moved into DE.
	2B		DCX H	
	E5		Push H	Adr. of next lower channel stored on stack
	6F		MOV L, A	Ch. no. is moved into L
	F5		Push PSW	
	CD F0 08		Call FLOAT	Convert fixed binary, in DE, to floating no. in CDE. Decrement C three times (divide by 8)
	0D		DCR C	
	0D		DCR C	
	0D		DCR C	
	CD E8 06		Call DATR 1	Data reduction performed
	C5		Push B	data in L. CDE is retained on stack
	25		Push D	
	E5		Push H	
	CD 61 07		Call DCML	Converts L, CDE to fixed decimal
	CD E3 07		Call THPTR	
	CD 91 07		Call TYPTR	
	F1		POP H	
	D1		POP D	Restores binary data
	C1		POP B	
	3A 00 1C		LDA PORT 1C	Check port 1C data
	F6 0F		ANI 0F	Test byte 0000/1110
06BD	CC 9A 05		CZ SETLO	If $C_1 + C_2 + C_3 = 0$, set L.O. = 0
06C0	F1		POP A	Restore A, H and L
	F1		POP H	
	3D		DCR A	Decrement counter
	C2 99 06		JNZ RUN 2	
	21 00 1F		LXI H, 1F 00	Advances the thermal printer and gives a linefeed on the terminal.
	11 FF FF		LXI D, FF FF	
	CD E3 07		Call THPTR	
	CD FF 01		Call 01 FF	
06D2	C9		RET	

Table A.12. DATRD – Reads the results of the last channel read by the A/D converter. Returns the answer in L (channel no.), and CDE (floating binary no.) may or may not be linearized

Addr	Mac. Lan.	Label	Code Op.	Comments
06D3	21 20 1C 4E 0D C2 DD 06 0E 17	DATRD	LXI H, Ch. No. Adr. MOV C, M DCR C JNZ CONT	The ch. no. adr. is loaded into HL Ch. no. is loaded into C decremented to get the last reading. C is set to 23 if ch. no. is 0 when decremented.
06DD	06 00 09 09 5E 23 56 69 CD E0 08	CONT	MVI B, 00 DAD B DAD B MOV E, M INX H MOV D, M MOV L, C	B is zeroed HL now contains ch. no. adr. + next ch. no. The last value read is moved into DE. L now contains the ch. no.
06E8	3A 00 1C E6 04 CC C8 05	DATR 1	CALL FLOT LDA PORT 1C ANI 04 CZ LINAR	Data is floated into CDE Data bit 1C ₂ is tested. Linearized if 0000/0100 byte = 0 Floating number in CDE and ch. no. in L are supplied to LINAR. The results are returned to the same registers
06F0	C9		RET	Return

Table A.13. CALIB – Calibration program, Strobes the A/D converter 23 or 24 times (depending on the front panel switches) and prints the last ch. which will be either the same ch. or one greater than the one read before.

Addr	Mac. Lan.	Label	Code Op.	Comments
06F1	0E 18 DB F6 E6 08 CA FF 06	CALIB	MVIC, 18 INPUT PORT 1C ANI 08 JZ CONT	Load counter into C (24 decimal) Input port 1C Test 1C ₃ bit Skip one count if 1C ₃ = 0 (low)
06FA	C5 CD 12 07 C1	LOOP	Push C Call ADRED POP C	Save C on stack Strobe A/D converter Restore C
06FF	0D C2 FA 06 CD D3 06 CD 61 07 CD E3 07 CD 91 07	CONT	DCR C JNZ LOOP Call DATRD Call DCML Call THPTR Call TYPTR	Decrement C Loop back 23 or 24 times Read the results of the last ch. Convert from binary to decimal Print results on thermal printer Print results on terminal
070F	C3 3E 04		JMP MANCT	Jump back to the main control program

Table A.14. ADRED – Reads the A/D converter, increments the channel, and starts the next conversion.
Stores the data in memory, sets channels to A/D converter

Addr	Mac. Lsn.	Label	Code Op.	Comments
0712	DB F5 E6 40 C2 12 07 CD 6D 06 21 20 1C 7E	ADRED	INPUT PORT 1B ANI 40 JNZ ADRED Call TIMER LXI H, Ch. No. Adr. MOV A, M	Look at 1B ₀ bit to see if A/D converter is busy (1B ₀ hi). Stay in this loop until it is low (0). Insert a time delay Load the ch. no. adr. in HL Load ch. no. into A
0720	4F FE 17 D2 2A 07 3C C3 2C 07		MOV C, A CPI 17 JNC RSCH INR A JMP CONT	Store in C also Compare to 23 Jump around if > 23 Increment ch. no. Jump around to CONT
072A	3E 01	RSCH	MVI A, 01	Set ch. no. to 1 if > 23
072C	77 5F 06 00	CONT	MOV M, A MOV E, A MOI B, 00	Store new ch. no. in memory Store new ch. no. in E Zero B, BC now contains old ch. no.
0730	09 09 DB F4 77 23 DB F5 E6 3F EE 10 77 21 00 00		DAD B DAD B INPUT PORT 1A MOV M, A INX H INPUT PORT 1B ANI 3F XRI 10 MOV M, A LXI H, 00 00	The address in HL is now Ch. no. adr. + 2 x ch. no. (old) Input low order bits Store in ch. no. adr. + 2 x ch. no. Increment HL pointer Input high order byte Dump 2 highest bits Complement byte 0001/0000 Store in ch. no. adr. + 2 x ch. no. + 1 Zero HL
0740	44 37		MOV B, H STC	Zero B Carry is set
0742	7D 17 6F 7C 17 67 78 17	BISET	MOV A, L RAL MOV L, A MOV A, H RAL MOV H, A MOV A, B RAL	Move L into A The "on" bit is rotated from The carry through L, H, and B
074A	47		MOV B, A	
074B	1D C2 42 07 7D		DCR E JNZ BISET MOV A, L	Decrement channel no. Jump back if not zero The high channel (in BHL) is
0750	D3 DC 7C D3 DE 78 D3 DE 3E 70 D3 F6 3E 30 D3 F6		OUT PORT 3A MOV A, H OUT PORT 3B MOV A, B OUT PORT 3C MVI A, 70 OUT PORT 1C MVI A, 30 OUT PORT 1C	sent to ports 3A ₀ - 3C ₀ Move H into A Output to port 3B Move B into A Output to port 3C The A/D converter is strobed high, then set back low, starting a new conversion
0760	C9		RET	Return

Table A.15. DCML - Takes a floating point number in CDE, ch. no. in L. Converts it into fixed decimal no. in CDE; exponent & sign in H, decimal ch. no. in L.

Add	Mac. Lan.	Label	Code Op.	Comments
0761	E5	DCML	Push H	Save L on the stack
	79		MOV A, C	Put sign of no. into H and dump sign
	F6 80		ANI 80	Load 20 complement
	C6 20		ADI 20	into H
	67		MOV H, A	
	79		MOV A, C	Move C into A
	F6 7F		ANI 7F	Dump sign
	4F		MOV C, A	Move A back into C
	E5		Push H	Store H on stack
	FE 48		CP 48	See if the exponent is > 48
076F	D2 7E 07	LOOP 1	JNC LOOP 1	Jump to loop 1 if exponent is > 48
	E1		POP H	If exponent is < 48,
	25		DCR H	decrement H twice.
	25		DCR H	
	E5		Push H	Store back on stack
	21 00 64		LXI H, 64 00	Load 100 into BHL
	06 48		MVI B, 48	
	CD 7B 09		Call EMPY	Multiply by 100
077E	CD B3 08		Call FIX	and then fix no.
	CD 33 0A		Call BIDEF	Convert to decimal
	E1	LOOP 2	POP H	Restore H from stack
	7C		MOV A, H	Retain in A while L
	E1		POP H	is being retrieved
	67		MOV H, A	
	AF		XRA A	Zero A and convert
0789	3C		INR A	L to decimal, using
	27		DAA	a simple counter
	2D		DCR L	
	C2 89 07		JNZ LOOP 2	
	6F		MOV L, A	H = sign & exponent, L = ch. no.
0790	C9		RET	Return

Table A.16. TYPTR - Terminal print subroutine. Put decimal in the proper place. Blank if L contains zeros. H contains exponent and sign. L contains ch. no.

Add	Mac. Lan.	Label	Code Op.	Comments
0791	E5	TYPTR	Push H	Save H & L registers
	C5		Push B	Save B & C registers
	7D		MOV A, L	Put L into the accumulator and
	FE 00		CPI 00	see if it contains a ch. no.
	C4 C3 02		CNZ 02 C3	Call monitor output routine
	0E 20		MVI C, 20	Load space character into C
	C4 E3 01		CNZ 01 E3	Print a space
	7C		MOV A, H	
	E6 80		ANI 80	Blank all except sign bit
	CA A6 07		JZ CONT 2	
07A1	0E 2D	CONT 2	MVI C, 2D	Print a space if +; print - if
07A6	CD E3 01		Call 01 E3	negative
	C1		POP B	Restore B and save
	C5		Push B	on stack
	79		MOV A, C	
	FE 00		CPI 00	
	C4 C3 02		CNZ 02 C3	Print B if not = 0
07B1	7A		MOV A, D	Load D in the accumulator
	CD C3 02		Call 02 C3	Print D
	0E 2E		MOV C, 2E	Load decimal point into C
	7D	CONT 3	MOV A, L	Load L back into A
	FE 00		CPI 00	Test for zero
	CA CD 07		JZ CONT 3	
	CD E3 01		Call 01 E3	Print decimal point if L is not 0
07C0	7B		MOV A, E	
	CD C3 02		Call 02 C3	Print D
	7C		MOV A, H	Dump sign
	E6 7F		ANI 7F	
	0E 20		MVI C, 20	Load a blank into C
	DE 1E		SBI 0E	Subtract 0E from A
	CA DD 07	POS	JZ RETN	Jump to RETN if zero
	D2 D5 07		JNC POS	Jump around if pos.
07D1	2F		CM A	Complement A
	3C		INR A	Increment A
	0E 2D		MVI C, 2D	Load 2D into C
97D5	F5		Push PSW	Save A on the stack
07DG	CD E3 01		Call 01 E3	Print - or blank
	F1		POP PSW	Restore A
	CD C3 02		Call 02 C3	Print exponent if not 0
07DD	CD FE 01	RETN	Call 01 FE	Line feed, carriage return
	C1		POP B	Restore B
	E1		POP H	Restore H
07E2	C9		RET	Return

Table A.17. THPTR - Thermal printer subroutine. Prints the sign in H, ch. no. in L, and decimal no. in CD

Add	Mac. Lin.	Label	Code Op.	Comments
07E3	DB F5	THPTR	IN PORT 1B	Check 1B ₀ bit to see if the thermal printer is busy
	07		RLC	(1B ₀ is high if busy)
	DA F3 07		JC THPTR	
	7A		MOV A, D	Move D into A and output
	D3 FD		OUT PORT 2B	to port 2B.
	7B		MOV A, F	Move F into A and output
	D3 FC		OUT PORT 2A	to port 2A
	7C		MOV A, H	Move H into A
	2F		CM A	complement A and dump all except
	E6 80		ANI 80	the sign bit (1 = + now)
	85		ADD L	Add the ch. no. and send to port 2C
	D3 FE		OUT PORT 2C	
	C6 40		ADI 40	Strobe the 2C ₀ bit high, then
	D3 FF		OUT PORT 2C	back low to initiate
	DE 40		SBI 40	a print command.
	D3 FE		OUT PORT 2C	
07FE	C9		RET	Return