**CODE DEVELOPMENT AND ANALYSIS PROGRAM
EMBRITTLEMENT OF ZIRCALOY CLADDING
DUE TO OXYGEN UPTAKE
(CBRTTL)**

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INTERIM REPORT

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A MODEL FOR
EMBRITTLEMENT OF ZIRCALOY CLADDING DUE TO OXYGEN UPTAKE
(CBRTTL)

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FOREWORD

This report describes a model for embrittlement of zircaloy due to oxygen uptake at high temperatures. It will become part of the Materials Properties (MATPRO)^[1] Handbook used in the fuel rod behavior modeling task performed at EG&G Idaho, Inc.

The model defines limits for oxygen content and temperature which, if exceeded, give rise to zircaloy cladding which is sufficiently embrittled to cause failure either on quenching or normal handling following a transient. A significant feature of this model is that the onset of embrittlement is dependent on the cooling rate. A distinction is made between slow and fast cooling, with the boundary at 100 K/s.

The material property correlations and computer subcodes described in MATPRO are developed for use in Light Water Reactor (LWR) codes. This work is being performed as part of the broad effort to develop and verify analytical models capable of describing nuclear fuel rod behavior.

A MODEL FOR EMBRITTLEMENT OF ZIRCALLOY CLADDING
DUE TO OXYGEN UPTAKE (CBRTTL)

One of the modes of cladding failure is by embrittlement, whereby failure occurs at low temperature with no plastic strain. This is because cladding ductility is reduced by oxygen uptake, especially after a high temperature excursion. Several hypothetical reactor transients can cause cladding to reach the high temperatures necessary for extensive oxygen diffusion. These transients include Power Cooling Mismatch, Reactivity Insertion, and Loss of Coolant. In the cooling following these transients, the cladding will be subjected to thermal stresses which may cause its fragmentation. Therefore oxygen embrittlement is an important safety consideration.

1. SUMMARY

The physical cause of this embrittlement is thought to be the presence of a phase nearly saturated with oxygen. A model is presented in this report defining limits for the amount of oxygen which may diffuse into zircaloy without causing it to become embrittled. The model has been formalized into a subcode designated CBRTTL.

The CBRTTL model deals with cladding which has reached a temperature of at least 1244 K, the point at which zircaloy has completed the phase transition from its low temperature hexagonal close packed structure, called the alpha phase, to a body centered cubic structure called the beta phase. This threshold is chosen because oxygen uptake increases exponentially with temperature and, except for time periods much longer than postulated for transients, not enough oxygen to cause embrittlement will diffuse into the cladding until beta temperatures are reached.

The model is divided into two parts to account for both fast and slow cooling rates. Fast cooling results in a different microstructure than does slow cooling. For example, acicular precipitates and "incursions" of oxygen stabilized alpha into the prior beta region are often found to occur after slow cooling but not after fast cooling^[4].

1.1 Oxygen Embrittlement of Fast Cooled Cladding

For fast cooling rates (> 100 K/s) such as are found following film boiling, the cladding is characterized as embrittled if:

- (a) the oxygen concentration in the beta phase is greater than 90 percent of the saturation concentration at the beginning of the fast quench,
- (b) the average oxygen concentration in the beta phase exceeds 0.65 percent by weight, or
- (c) the maximum temperature exceeded 1700 K.

The first two of these restrictions are of the type proposed by R. E. Pawel of Oak Ridge National Laboratory^[4] (ORNL). The last is based on data obtained at the INEL^[5].

1.2 Oxygen Embrittlement of Slow Cooled Cladding

During a transient such as a LOCA, there are two cladding cooling rates. One is the rather slow rate during refill and the other is the rapid rate due to quench. If the slow decrease brings the cladding below the temperature of the beta phase, it is this rate that is important for embrittlement. In these cases the cladding is characterized as embrittled if 0.3 mm or more of the beta phase contains more than 1 percent oxygen by weight. This criterion is similar to one proposed by T. F. Kassner et al^[6] of Argonne National Laboratory (ANL).

The input required by CBRTTL are the temperature and oxygen profiles in the beta phase zircaloy. At the INEL, these are found with the FRAP codes^[2,3] in conjunction with the COBILD high temperature oxidation subcode from the MATPRO Handbook^[1]. When the oxygen concentration exceeds the limits defined above, the subcode returns a non-zero value for CBRTTL signifying that the cladding is critically embrittled.

Section 2 of this report contains a discussion of the literature reviewed. The model development is presented in Section 3 along with model-data comparisons and a discussion of the uncertainty. The FORTRAN subcode is given in Section 4 and the References in Section 5.

2. LITERATURE REVIEW

The paper by Pawel^[4] is the basis for the part of CBRTTL describing fast cooled cladding. The criteria presented by Pawel are modified based on in-pile data taken at the INEL^[5]. The embrittlement criterion for slow cooled cladding is based on data taken from a recent series of reports from ANL^[6,7,8]. The data sets are described in Sections 2.1 and 2.2 respectively.

2.1 In-Pile Data for Fast Cooling

Data taken in-pile at the Power Burst Facility (PBF) reactor of the INEL are extensively documented in a recent report^[5]. In this reactor fuel rods about three feet in length but otherwise of typical PWR dimensions are subjected to film boiling for controlled periods. The rods are externally pressurized to obtain a pressure differential of at least 10 MPa. The oxidizing agent is steam since data were taken from areas experiencing film boiling and the rods were oxidized under non-isothermal conditions. In some cases the cladding temperature varied by as much as 800 K during a single experiment. Such temperature fluctuations provide an ideal test for the COBILD model. Another important feature of the PBF tests is that the source of heat was actual fuel pellets, that can relocate causing typical pellet-cladding thermal and mechanical interactions.

A major disadvantage of the PBF data base is that it is quite small. More experiments are planned to enlarge this data base. Competing embrittlement effects, such as chemical reactions at the inside surface from pellet-cladding interaction and aggressive fission products, present another difficulty. The fact that the PBF data conform well to Pawel's criteria developed from data taken out-of-pile^[9], where such competing

effects are absent, suggests that this latter disadvantage may not be important and that oxygen uptake is the dominant embrittlement process.

2.2 Out-of-Pile Data for Slow Cooling

Many out-of-pile data were taken from recent reports by H. M. Chung, A. M. Garde, and T. F. Kassner^[6,7,8]. The samples were 30 cm zircaloy tubes with inner and outer diameters typical of light water reactor cladding. About one-half of the tube length was filled with alumina (Al_2O_3) pellets to simulate the fuel. The experimental procedure was to heat the sample by induction heating to the test temperature from room temperature at 10 K/s. This temperature was held for the desired time period after which the sample was cooled at 5 K/s to approximately 810 K, and then rapidly quenched by bottom flooding with water. The tubes ruptured during the heating phase due to an initial internal pressure, typically about 7 MPa. During the entire experiment a steam generator circulated steam at about 0.15 MPa pressure past the specimen. After each experiment the tubes were examined and classified in one of three ways:

- (a) tubes which failed during the quench,
- (b) tubes which survived quench but failed in "normal handling" required to remove them from the experimental apparatus, and
- (c) tubes which remained intact.

The Argonne experiments provide a good test of the ability of zircaloy cladding, embrittled by nearly isothermal oxidation, to withstand the thermal shock of reflood after a hypothetical LOCA. The principal disadvantage of these tests is that the alumina pellets may not apply the same stresses as cracked and relocated fuel.

3. MODEL DEVELOPMENT

Ideally, a model for embrittlement by oxygen uptake would specify a maximum acceptable stress or strain as a function of oxygen content in the cladding. The available data however, are not amenable to such an approach because neither the stress nor the strain at failure are measured. For some cases the stress or strain could be calculated, but this is clearly not possible for those rods which failed during "normal handling" at Argonne. Therefore a more empirical process is used, wherein several commonly used embrittlement criteria are tested against the data, and the most appropriate ones subjected to sensitivity studies to determine the best boundary conditions.

3.1 Evaluation of Possible Embrittlement Criteria

Several embrittlement criteria are now in use or have been proposed. In this subsection the more prominent ones are compared to the data. The COBILD code is used to calculate oxide layer thicknesses, oxygen uptake, and oxygen profiles in the beta phase since this subcode will be used by the FRAP-T code.

3.1.1 Presently Used Acceptance Criteria. For reactor licensing purposes the present oxidation limits for an acceptable emergency core cooling system are defined in the Code of Federal Regulations, Title 10, Section 50. The code specifies:

- (a) that the peak cladding temperature must not exceed 2200°F (1477.5K) and
- (b) that the oxide thickness which would result if all the oxygen uptake produced ZrO_2 , (called the "equivalent cladding reacted"), must not exceed 17% of the original cladding wall thickness.

Both of these criteria have been shown to be conservative for out-of-pile tests^[6,8] and inconsistent for in-pile tests^[5].

3.1.2 Fraction of Wall Thickness Which is Beta Phase Criterion.
Scatena^[10] suggested an embrittlement criterion based on the quantity F_w , where

$$F_w \equiv \frac{\text{remaining beta phase thickness}}{\text{original unoxidized wall thickness}} \quad (1)$$

If $F_w \leq 0.5$, the material is considered embrittled. This criterion was not found to work well for either the out-of-pile or in-pile data, being conservative in both cases.

3.1.3 Argonne Impact Energy Criterion. In these tests the tubes were treated as described in Section 2.1. In an effort to quantify the embrittlement, those rods which emerged intact from quenching and handling were subjected to impact testing with a pendulum device. Impact energies of 0.03 Joules and 0.30 Joules were used, causing additional rods to fail. However, unless an allowable impact energy is specified, classification of tubes shattered by impact as "failed" is not meaningful. If such an energy is specified, an embrittlement model based on these data will become an attractive possibility.

3.1.4 ORNL Correlation of Embrittlement with Oxygen Content in the Beta Phase. Using data from a report by Hobson and Rittenhouse^[9], Pawel^[4] arrived at two embrittlement criteria for zircaloy. He considered the cladding embrittled if the oxygen content of the beta phase exceeded:

- (a) 95 percent of the saturation content, or
- (b) 0.7 percent by weight.

This model is slightly modified by changing the above limits to 90 percent of saturation or 0.65 percent by weight, and by adding a 1700 K limit to the cladding temperature. The saturation oxygen concentration is determined from a zircaloy-oxygen phase diagram published by Chung et al^[13].

3.1.5 Argonne Correlation of Embrittlement with Oxygen Content in the Beta Phase. Using a computer code developed at their laboratory, Chung et al^[6] found an embrittlement criterion which fits their data very well. Their criterion states that the cladding will not be embrittled if there is at least 0.1 mm of beta with less than 1.0 percent oxygen content by weight. A temperature of 1573 K or greater is necessary for the oxygen concentration in beta zircaloy to equal 1.0 percent. Therefore for temperatures less than 1573 K the entire thickness of the beta region must be at least 0.1 mm wide. The limits set by the Argonne group are consistent with the conclusions of a more qualitative study by A. Sawatzky^[11], who states that the maximum temperature and total oxygen content have little or no effect on the tensile properties of zircaloy-4. Sawatzky used a maximum cooling rate of 160 K/s for about 10% of his samples, but the other 90% were cooled at rates of 21 K/s or less so his conclusions apply primarily to slow cooled cladding. The Argonne model is modified by increasing the minimum thickness with less than 1.0 percent oxygen to 0.3 mm.

3.2 CBRTTL Model for Fast Cooled Cladding

The Pawel^[4] criteria, slightly modified and with the additional limit that the peak cladding temperature must not exceed 1700 K, are adopted for the fast cooled cladding model. Physically, a percent saturation limit makes sense, at least qualitatively, because as the oxygen content of the beta approaches saturation, the oxygen excess is relieved by the formation of brittle oxygen-stabilized alpha precipitates, often in the form of incursions originating in the normal alpha phase layer and extending into the beta. The presence of these oxygen rich alpha incursions is always associated with a loss of ductility. They may also form during cooling because as the temperature decreases so does the terminal oxygen solubility, often making the beta phase super-saturated with oxygen.

The second criterion, no more than 0.65 percent oxygen concentration by weight, is needed because the diffusivity of oxygen also decreases with temperature, and if the cooling rate is high enough there will not

be sufficient time for incursions to form during cooling, and only those formed at high temperature will be present. In addition, the ductility of zircaloy decreases even without incursions as its oxygen content increases so there must be a critical concentration in weight percent oxygen which causes embrittlement. The 1700 K limit, although in contradiction to the conclusions of Swatzsky^[11], is found to be necessary to fit the data.

Pawel's limits of 95 percent saturation and 0.70 weight percent oxygen, were subjected to a brief sensitivity analysis to examine the effect of varying these limits. Weight percents of 0.70 and 0.65 and percent saturations of 90 and 95 were tried. The results are shown in Figure 1, along with data from the Hobson-Rittenhouse experiment. This plot shows little to be gained by changing the limits. These criteria do not specify a single thickness for the beta layer necessary to retain ductility. However, for a given original wall thickness it is possible to find a critical beta thickness as a function of temperature corresponding to the limits of this model. This thickness is usually expressed as a ratio

$$(F_w)_{crit} = \frac{\text{critical thickness of beta layer}}{\text{original unoxidized wall thickness}} \quad (2)$$

A $(F_w)_{crit}$ criterion corresponding to limits such as those specified by Pawel is particularly useful because it contains no explicit reference to time and may therefore be generalized to more realistic situations where the rod temperature changes. Time is still a necessary parameter to make the calculations, but in the evaluation of the ductility only the oxygen content and the temperature at a time are required. For this part of the model the time and temperature used are those at the end of the last time-temperature segment when the cladding was entirely in the beta phase. In Figure 2, $(F_w)_{crit}$ is plotted as a function of temperature. The solid lines are for 0.7 weight percent and 95 percent filled, and the dashed lines are for 0.65 weight percent and 90 percent filled.

Fig. 1 Hobson-Rittenhouse isothermal data for fast cooled cladding compared with the 0.65 and 0.70 weight percent and the 90 and 95 percent filled criteria.

Fig. 2 Hobson-Rittenhouse and PBF data for fast cooled rods compared with the critical fractional wall thickness as calculated from the 0.65 and 0.70 weight %, and 90 and 95% filled criteria.

Also shown in the figure are data from the Hobson-Rittenhouse out-of-pile isothermal tests and the in-pile PBF non-isothermal tests. All the points, as well as the limiting lines, were calculated with the COBILD subcode. As with Figure 1, the data apply for a specific wall thickness, chosen here to be 0.60 mm to correspond to the PBF data. However COBILD runs show that the limiting lines in Figure 2 move less than one percent when the wall thickness changes by as much as 40 percent from 0.60 mm.

An obvious feature of this figure is that three in-pile rods failed when they apparently should not have. These rods were at temperatures of 1405, 1418, and 1523 K. Post irradiation examination of the inner surface oxidation showed that these rods had a wall defect in the vicinity of the failure, allowing steam to enter. Hot zircaloy exposed to stagnant steam will absorb an abnormally large amount of hydrogen^[12], and the failures of these three rods show evidence of hydride influence^[5]. These rods are therefore not deemed suitable examples of the more simple failure by oxygen embrittlement.

It is also clear from the figures, especially Figure 2, that the lower limits of 90 percent saturation and 0.65 weight percent oxygen include more of the failed rods than do Pawel's original limits. Neither set of criteria predicts a failure for a rod observed to remain intact.

Consequently, the model for fast cooled cladding is that the cladding is considered embrittled if the oxygen content of the beta phase exceeds

- (a) 90 percent of the saturation content, or
- (b) 0.65 percent by weight.

A third criterion limiting the maximum cladding temperature to less than 1700 K is added to these to fit the highest temperature data.

The data are still too few to consider this model final. But the accuracy is encouraging, especially considering the differences in the experiments. The Hobson-Rittenhouse samples were oxidized on both

sides, out-of-pile, and quenched rapidly while the PBF samples were oxidized primarily on the outside, in-pile, and quenched more slowly.

3.3 CBRTTL Model for Slow Cooled Cladding

Designating this part of the model as applying to slow cooled cladding is slightly misleading. It is meant to apply during the pre-quench of a LOCA. As described in Section 2.2 of this report, Chung, Garde, and Kassner^[6,7,8] have completed many out-of-pile tests of this sort and developed an embrittlement criterion requiring at least 0.1 mm of cladding thickness with less than 1 percent oxygen content by weight. When this criterion was checked using COBILD it was found that at least 0.3 mm with less than 1 percent oxygen by weight is required to avoid failure by thermal shock. No reason for the difference between this and the Argonne minimum thickness of 0.1 mm has been found. It possibly lies in the mechanics of the two codes. When the Argonne code is more fully documented this can be checked. Until then the criterion established with COBILD will be recommended for use with the MATPRO package.

In Figure 3 this criterion is compared with the data. Only temperatures greater than 1244 K are considered, since this is the lower range of validity for COBILD. Not all of the data are shown in the figure because many are coincident or nearly so. Of the 146 intact rods, 16 or 11 percent, are predicted to fail and of the 57 failed rods, 4 or 7 percent are predicted to remain intact. In the entire data set, less than 10 percent of the predictions are incorrect. Given the scatter in the data, this is considered acceptable accuracy.

Since all the tubes tested at Argonne had a wall thickness of 0.635 mm, it is impossible to conclude whether the 0.30 mm is the actual minimum thickness required to retain ductility, or if there is some minimum F_w . The former is more reasonable on physical grounds because it seems logical that there should be a minimum thickness of ductile material necessary for ductility.

Fig. 3 Comparison of the Argonne data for slow cooled cladding with the criterion that at least 0.3mm of zircaloy with less than 1% oxygen by weight is required to survive thermal shock.

If the embrittlement criteria for fast cooled rods are compared with the slow cooled data, failure would be predicted in most cases, contrary to experimental observation. Similarly the criterion used for the slow cooled rods almost never predicts a failure when compared to the fast cooled data. These facts underscore the importance and complexity of cooling rate on the ductility of zircaloy oxidized at high temperature, and further emphasize the importance of clearly specifying the cooling rate.

3.4 Uncertainty of the Models

A primary source of uncertainty for both models is in temperature measurement. For the Hobson-Rittenhouse data set the temperature uncertainty is estimated by comparing the temperature reported for a given layer thickness with that calculated using isothermal oxidation kinetics published by Cathcart et al^[15] for the same thickness. From this analysis the root mean square of the temperature differences is about 50 K. A similar technique was used for the PBF and Argonne data. Seiffert and Hobbins^[5] also arrived at an uncertainty of about 50 K, while Chung et al^[7] found an 85 K uncertainty. This technique should give a reasonable estimate because Cathcart's correlations are based on a careful analysis of his own data. This analysis shows the data to have a high degree of consistency, and the major error in measurement should be the temperature, the layer thicknesses being much easier to obtain with accuracy.

There is another potentially important source of systematic error in the Argonne data. They were presented in graphical rather than tabular form. A digitizer was used to obtain numerical values. The data were generally plotted as the logarithm of the time versus reciprocal temperature, so larger errors result for long times or high temperatures. By repeating the digitizing from the same plots the uncertainties listed in Table I were found.

TABLE I
UNCERTAINTIES IN DIGITIZED ARGONNE DATA

Temperature	Δ Temp	Time	Δ Time
1250 K	16 K	10^2 s	2.5s
1650 K	28 K	10^4 s	2.50s

An idea of the effect of errors for fast cooled cladding may be obtained by examining Figure 1. For slow cooled cladding a sensitivity analysis is required to find what change in beta phase thickness with less than 1 percent oxygen content would result from the given uncertainties. Such an analysis has not been carried out since the Argonne group plans to publish their data soon, eliminating the digitizing errors and thus allowing a more accurate analysis.

4. LISTING OF THE CBRRTL SUBCODE

A listing of the cladding embrittlement subcode is given in Table II.

TABLE II

LISTING OF THE SUBCODE CBRTTL

FUNCTION CBRTTL(AM5,Y8,Y88,Y9,Y99,Y100,CTEMP,BWTFRO,RCOOL,AA1,
AB1,AC1,AD1,AE1,AF1,AG1,AH1,AI1,S)
THE FUNCTION CBRTTL DESCRIBES THE ONSET OF ZIRCALOY CLADDING
EMBRITTEMENT BY OXYGEN ABSORPTION.

CBRTTL = OUTPUT CLADDING EMBRITTEMENT INDEX. IF CBRTTL
.GT. 0.0 THE CLADDING IS CONSIDERED BRITTLE.

AM5 = INPUT ORIGINAL CLADDING CLADDING WALL THICKNESS (M).

Y8 = INPUT OUTSIDE OXIDE THICKNESS (M).

Y88 = INPUT INSIDE OXIDE THICKNESS (M).

Y9 = INPUT OUTSIDE OXYGEN STABILIZED ALPHA THICKNESS (M).

Y99 = INPUT INSIDE OXYGEN STABILIZED ALPHA THICKNESS (M).

Y100 = INPUT SUM OF OTHER INSIDE LAYERS (M).

CTEMP = INPUT CLADDING TEMPERATURE (K).

BWTFRO = INPUT CLADDING AVERAGE OXYGEN CONCENTRATION IN EXCESS
OF AS-FABRICATED AMOUNT (WEIGHT FRACTION).

RCOOL = INPUT COOLING RATE BEFORE QUENCH (K/S).

AA1-AI1 = INPUT OXYGEN CONCENTRATIONS IN PRIOR BETA AT NINE
EQUIDISTANT NODES. AA1 IS THE CONCENTRATION AT THE
BETA/ALPHA+Beta INTERFACE AND AI1 IS THE
CONCENTRATION AT

A) THE INNER CLADDING SURFACE FOR OUTSIDE OXIDATION
ONLY, OR

B) THE MINIMUM CONCENTRATION FOR TWO-SIDED OXIDATION
(WEIGHT FRACTION).

S = INPUT INDEX, 1.0 FOR OUTSIDE OXIDATION ONLY,
2.0 FOR TWO-SIDED OXIDATION.

THE CORRELATIONS USED IN THIS FUNCTION ARE BASED ON THE
FOLLOWING REFERENCES.

(1) R.E. PAWEL, JOURNAL OF NUCLEAR MATERIALS, 50 (1974)

(2) H.M. CHUNG, A.M. GARDE, AND T.F. KASSNER --

A. ANL-78-49 (JUNE 1978).

B. ANL-78-3 (JANUARY 1978).

C. ANL-78-25 (MAY 1978).

(3) D.O. HOBSON AND P.L. RITTENHOUSE, ORNL-4758 (JAN. 1972).

(4) S.L. SEIFFERT AND R.R. HOBBS, TFBP-TR-292 (OCTOBER 1978).

CBRTTL WAS ORIGINALLY CODED BY G.A. REYMAN IN FEB. 1979.

DIMENSION AN(9)

IF(CTEMP .LT. 1244.0) GO TO 100

CBRTTL = 0.0

IF(RCOOL .GT. 100.0) GO TO 50

LOW COOLING RATE CALCULATION

AN(1) = AA1

AN(2) = AB1

AN(3) = AC1

AN(4) = AD1

AN(5) = AE1

AN(6) = AF1

AN(7) = AG1

TABLE II (cont)

LISTING OF THE SUBCODE CBRTTL

```

C      AN(8) = AH1
C      AN(9) = AI1
C      Y2 = (AM5 - 2.*(Y8+Y88)/3. - (Y9+Y99) - Y100)*100.0/8.0
C      Y2 = INTERNODAL SPACING IN THE BETA.
C      IF(AN(1) .LT. 1.0E-02) GO TO 20
C      DO 10 J = 2,9
C          K=J
C          IF(AN(J) .LT. 1.0E-02) GO TO 15
10      CONTINUE
C      ANUMB = 9.0 - FLOAT(K)
C      BCRIT = BETA THICKNESS WITH LESS THAN 1.0% OXYGEN BY WEIGHT.
C      BCRIT = ANUMB*Y2 + ((.01-AN(K))/(AN(K-1)-AN(K)))*Y2
C      GO TO 25
20      BCRIT = 8.0*Y2
C      BCRIT = S*BCRIT
25      IF(BCRIT .LT. .03) CBRTTL = 1.0
C      GO TO 100
C
C          HIGH COOLING RATE CALCULATION
C
50      IF(CTEMP .GT. 1700.0) CBRTTL = 1.0
C      IF(CTEMP .GT. 1700.0) GO TO 100
C      BCON = (BWTFRD + 0.0012)*100.0
C      BCON = AVERAGE CONCENTRATION IN THE BETA (WEIGHT PER CENT).
C      IF(BCON .GT. 0.65) CBRTTL = 1.0
C
C          CALCULATION OF SATURATION CONCENTRATION IN THE BETA FOLLOWS.
C
C      SAT = 0.12
C      SAT = SATURATION CONCENTRATION IN THE BETA (WEIGHT PER CENT).
C      IF(CTEMP .LT. 1239.0) GO TO 55
C      SAT = -4.287E-03 + SQRT((CTEMP/392.46)-3.1417)
C      IF(CTEMP .LT. 1373.0) GO TO 55
C      SAT = (CTEMP-1081.7)/491.157
55      CONTINUE
C      BSAT = 1.0E04*(BWTFRD+.0012)/SAT
C      BSAT = PER CENT OF SATURATION CONCENTRATION IN THE BETA.
C      IF(BSAT .GT. 90.0) CBRTTL = 1.0
C
100     CONTINUE
C      RETURN
C      END

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5. REFERENCES

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