SODIUM VALVE ANALYSIS CRITERIA
AND METHODS

For Presentation at International Specialists Meeting on "Operating Experience and Design Criteria of Sodium Valves", Sponsored by the International Working Group on Fast Reactors of the International Atomic Energy Agency.

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1.0 INTRODUCTION
The purpose of this paper is to summarize state of the art in the United States of structural criteria and analytic methods applicable to sodium valves. First, the structural criteria to which sodium valve pressure boundaries must conform will be described, to include some amount of historical development in this area. Secondly, analysis methods will be described to include summary descriptions of the most pertinent available analytic tools (structural, thermal, and hydraulic) and several examples of sodium valve analytic results.

2.0 STRUCTURAL CRITERIA
Figure 1 tabulates previous and currently applicable structural design criteria. The first national criteria for nuclear components was Section III of the ASME Boiler and Pressure Vessel Code, "Rules for the Construction of Nuclear Vessels," published in 1964. Emphasizing the criteria which were applied to sodium valves of recent manufacture, the table begins with the 1967-1968 time frame. The 1968 Edition of Section III provided structural criteria only for temperatures below which time-dependent effects, e.g., creep, are not important; this is also the case for the 1971 and 1974 editions of the basic Section III. The vehicle for criteria for high temperature, above 800°F for austenitic steels, has been the so-called "high temperature Code Cases." The first such Code Case of interest in our discussion is Code Case 1331-4 which provided minimal guidance, consisting of two pages of text and two design fatigue curves. Lacking the availability of more comprehensive criteria for high temperature design, the Westinghouse Advanced Reactors Division (ARD) issued FRA 152, a fairly comprehensive set of interim design rules. The set of criteria which applied to nuclear sodium valves recently completed or in the final stages of fabrication (like the Fast Flux Test Facility (FFTF) components, and equipment used in recent Liquid Metal Engineering Center (LMEC) and Hanford Engineering Development Laboratory (HEDL) facility construction) are the 1971 edition of Section III, high temperature Code Case 1331,-5 or later, and a United States Atomic Energy Commission (AEC) Standard, RDT F9-1T. RDT F9-1T is a 42-page document which supplements Code Case 1331 in the areas of permanent strain limits, limitations on use of simplified inelastic analysis methods, form of the stress-strain relationships for elastic-plastic-creep behavior, and non-
mandatory material on simplified screening analysis methods and on available
computer programs. AEC Standard-RDT-E1-18T, "Class I Valves for Liquid Metal
Service," is not listed in the table because the bulk of its guidance is
devoted to other than design analysis matters. The set of criteria for
components currently in the ordering stages consists of the 1974 Edition of
Section III, Code Cases 1592 through 1596, and RDT Standard F9-4T (mandatory)
and F9-5T (non-mandatory).

Figure 2 simply provides the full titles of the documents described in
abbreviated form on Figure 1.

2.1 ASME Criteria
In beginning a discussion of the criteria as issued by the American Society
of Mechanical Engineers, the original foundations of the ASME Boiler and
Pressure Vessel Code, Section III, should be reviewed. These are provided
on Figure 3. The provisions of Section III are more consistent with the
capability which was reached in stress analysis state of the art by the 1960's
to perform dependable and efficient calculations of stresses in considerable
detail. This more detailed knowledge allowed more realistic stress limits
with no diminution of margin of safety in vessels. This allowed for a set
of stress limits rather than a set of gross rules of allowable geometry. A
major concern in the preparation of Section III was the need for superior
vessels (pressure boundaries) for nuclear service because of the consequences
of nuclear vessel failure, the difficulty of inspection, and the more demanding
service (extended life with little or no maintenance and highly cyclic operation).
Much of the "design by analysis" flavor of Section III is also present in
Division 2 of Section VIII, alternate rules for non-nuclear vessels.

A general impression of the philosophy of Section III and level of conser-
vatism can be gained from a review of the basic stress intensity limits
for design conditions (conditions prescribed in the equipment specification
to guide the design) and normal plus upset conditions (expected operating
conditions, including abnormal events of moderate likelihood of occurrence).
These are shown on Figure 4 in terms of the most important stress types
versus $S_m$, the Code allowable stress intensity. Code allowables are, of
course, generally associated with stress intensity, which is the largest
difference between principal stresses, that is, twice the maximum shear stress
at a point.
Moving from the basic Section III, the coverage of which is restricted to temperatures below 800°F, to the high temperature Code Cases, the highlights of Code Case 1592 are listed on Figure 5. The contents of Code Case 1592 represents the culmination of high temperature criteria as they evolved through the series of 1331 cases. It is Code Case 1592 which guides the structural design of nuclear sodium components currently in the ordering process. The essence of the high temperature Code Cases is increased recognition of present day ability to dependably "design by analysis" and necessary supplementary provisions in recognition of time-dependent effects in the behavior of metals in the high temperature regime.

Figure 6 is the so-called "Hopper diagram" extracted from Code Case 1592. Some items to be noted are the designations $S_t$ and $S_{mt}$, indicating limits which account for time-dependent effects. $K_t$ corrects for geometry and the fraction of stress which is primary membrane. The time ratios, $t/t_m$ and $t/t_b$, imply usage factors not associated with fatigue, again a recognition of time-dependent effects even under static loading. Note the strain and deformation limits unique to the high temperature Code Cases. Cumulative permanent strain limits are seen to be 1%, 2%, and 5%, for membrane, linearized bending, and local strains, respectively. These particular limits are generally acknowledged to be highly judgmental. These deformation limits are intended to be used with the results of inelastic analysis. Limits are also provided based solely on elastic analysis, but can be expected to be more conservative. The limits at the bottom of the Functional Requirements block apply to usage factor limits for fatigue with creep taken into account and for buckling with creep taken into account.

On Figure 7 is shown a requirement of special applicability to this meeting, minimum wall thickness for valves. This limit replaces the more conservative wall thickness minima prescribed in Section III, paragraphs NB-3542 and NB-3543, which are geometric guidelines not associated with detailed stress levels as calculated for a specific application. The Figure 7 guidelines are more consistent with the current Code philosophy supporting "design by analysis." The origin of this wall thickness requirement is of historical interest. It arises out of an inquiry submitted to the ASME Code Committee by the Westinghouse ARD Valve Engineering department in 1972. The original
rules required too thick a wall to tolerate the Fast Flux Test Facility (FFTF) thermal transient stresses and more thickness than was required to safely carry the valve mechanical loads.

Strict adherence to the ASME Code numerical limits does not fully discharge the responsibility of the sodium valve designer/manufacturer. Figure 8 lists areas in which the valve supplier has independent responsibility, areas which are only qualitatively represented in the Code as high temperature component design considerations. The first item is proper accounting for the myriad of environmental effects. Component deformation as it affects proper functioning rather than structural integrity is listed next. Several items cover the very difficult problem of supplier development/selection of methods to evaluate non-linear effects. Finally, the supplier is invited to define alternate high temperature criteria if the published Code limits are judged to be inappropriate.

2.2 AEC Structural Standards

Class 1 nuclear components procured within the AEC LMFBR program are subject to additional structural criteria as represented by certain AEC standards. The two currently applicable AEC standards related to high temperature structural analysis are RDT Standards F9-4T and F9-5T (replacing an earlier document, F9-1T). Key elements of the documents are summarized on Figures 9 and 10. RDT F9-4T is a modest document (13 pages) which imposes additional conservatism, where judged advisable, over Code Case 1331 (and 1592) in several selected areas. RDT F9-5T has a different flavor and is essentially a high temperature structural criteria user assistance manual. Knowledgeable user representatives have collaborated closely with the AEC in preparing non-mandatory guidelines regarding organization and planning of the analysis, inelastic analysis methods, means of increasing analysis validity, and high temperature deformation behavior for metals of most immediate interest. RDT F9-1T also provides interpretations of the ASME Code limits and their mode of application.
3.0 ANALYSIS METHODS

The following discussion will cover structural, thermal, and hydraulic computational tools applicable to sodium valves. Examples of analysis models and results will also be described.

Figure 11 outlines the features of the six computer programs summarized in F9-5T and suited to sodium valve analysis, with special attention given to non-linear capability so important in the high temperature work. The first two programs, MARC and ANSYS, are the most nearly general programs in the group. A summary comparison of the two programs is that MARC allows for a more precise non-linear treatment with the option of significant user control over the computational relationships but requires a knowledgeable, experienced user. The ANSYS strength is in the obvious user orientation, exemplified by the automation available regarding both input model preparation and output graphics, and relative ease of partial model modification. CREEP-PLAST and EPACA are sound tools for problems which can be adequately addressed in two dimensions. The final two programs described, Foster Wheeler Program R-1045 and Basic Technology Program BT1511, are practically speaking one-dimensional programs, but do, within that geometric constraint, allow rigorous prediction of material behavior in the non-linear range, including cycles. The cost of analyzing sodium valves, especially those for high temperature service, has been significant. Equipment suppliers have every incentive to perform stress analysis in the most economic manner consistent with responsible engineering practice. This means application of the least sophisticated tool which provides satisfactory structural assessment. For example, three-dimensional elastic-plastic-creep analysis under cyclic loadings by means of MARC or ANSYS should be undertaken only after careful consideration of simpler options. Adequate analysis at minimum expense depends on engineering ingenuity. For example, three-dimensional elastic analysis results as computed by ANSYS for the FFTF hot leg isolation valve were used to provide boundary conditions for one-dimensional (actually hollow cylinder) representation of the critical location. The one-dimensional analysis was performed with the Foster Wheeler Corporation R-1045 program. The thermal and mechanical loading conditions at the critical location, as deduced from the elastic stress field in the three dimensional configuration, were reproduced by artificial temperature gradients, internal pressure, and
end tractions. A major concern in such simplifications of the problem is the matter of "elastic follow-up" or "strain concentration." Elastic follow-up refers to the potential for transferring strain energy preferentially to a single location. The result is a local concentration of plastic or creep strain. However, such innovations to reduce analysis costs are highly advantageous when applied with mature engineering judgement.

Figure 12 shows a sample ANSYS three-dimensional shell model as constructed by O'Donnell and Associates analysts. There are over 2000 elements in this model of the FFTF hot leg isolation valve, which Mr. Nulton discussed. Computer runs of this model were prohibitively expensive. After the initial run, future calculations performed within the Westinghouse Valve Engineering department to refine the design of the hillside penetration (a valve body penetration designed to accommodate the valve gate operator) were accomplished with the model in the blocked out area. The original model results provided guidance as to where three-dimensional effects disappeared and one had the condition of symmetry or long hollow cylinder-type behavior. This figure represents then a state-of-the-art finite element model as well as an imaginative way to economize follow-on calculations.

As another example, Figure 13 shows a finite element model of the FFTF hot leg isolation valve gate with the vertical axis lying on the valve and gate centerline. Two ANSYS graphical display output options are shown on Figure 14. The top picture shows gate displacements (not to scale) under closure loadings which bear on the gate center. The lower picture shows constant stress intensity lines plotted on the gate geometry. The minimum and maximum values are indicated.

Figure 15 shows the finite element model of the FFTF 8-inch secondary set/isolation valve, described earlier by Mr. Nulton. The internal stem support structure and seat portions of the model are shown alongside the valve body model. This analysis was performed for the Crane Company, the valve supplier, by Teledyne Materials Research Company. The ANSYS program was used.

Figures 16, 17, and 18 demonstrate three-dimensional finite element modeling of the Sargent Industries 4-inch isolation/flow control valve discussed in
Dr. McGough's paper. The analysis was performed by Basic Technology, Incorporated, using ANSYS. Figure 16 depicts the basic geometry of this valve body. The finite element model is shown in Figure 17. Figure 18 shows lines of constant membrane stress in the valve shell midplane.

Although, as implied by the figures just seen, the preponderance of the analysis on sodium valves of recent manufacture has been performed by means of the ANSYS program, portions of the various analyses have been performed by means of the less general programs summarized earlier and potential user familiarity with other programs is increasing.

In addition to analysis tools for thermal and structural evaluation of valves in high temperature service, tools are required for fluid dynamic analysis of check valves and otherwise fast-acting valves. No known general computer programs are known to exist which calculate fluid transient events such as "sodium hammer." A program with the acronym DACVA was developed by the Rockwell Manufacturing Company (and later modified by O'Donnell and Associates, Incorporated) to analyze the FFTF cold leg check valve under transient fluid dynamic conditions. The program is not an ideal, general purpose tool, unfortunately. Portions of the program are quite empirical and in fact certain of the analytic results represent disconcerting departures from experimental results. Moreover, the program is specifically written for the FFTF primary heat transport system and much of the internal logic is a representation of the FFTF primary loop component hydraulic characteristics. However, all in all, DACVA is judged to be a minimum adequate tool for dynamic evaluation of the FFTF primary check valve. A program to perform the same type of calculation is being developed at Bechtel Corporation to evaluate the effect of rapidly closing small valves in FFTF auxiliary piping systems.

Figure 19 summarizes the DACVA program. Key items of input are described. The major output items are a complete kinematic description of the disc and a pressure history on both sides of the disc. Before sample DACVA output is shown, the FFTF 16-inch check valve design will be briefly reviewed. Figure 20 shows the FFTF primary loop check valve. Its action follows the tilting disc principle. Figure 21 shows the dashpot, a closed-end cylinder with a spring-reacted piston.
Figure 22 shows the DACVA kinematic output for the following situation: Two of the FFTF primary pumps start at zero time. At 50 seconds, the third pump starts up but fails about five seconds into the startup. Dashpot and disc positions are plotted. Disc velocity and calculated pressure surges are indicated in the figure.

4.0 SUMMARY AND CONCLUSIONS
Criteria for structural design of sodium valves were described, both national commercial standards (ASME Boiler and Pressure Vessel Code) and AEC government standards (AEC RDT standards). Emphasis was on high temperature (above 800°F for austenitic stainless steels) rules since these are in a highly developmental stage. In addition to structural criteria, analytic methods were described for structural, thermal, and hydraulic analysis, with emphasis on the difficult phenomena requiring non-linear mathematical formulation. Examples of applications to the FFTF sodium valves were presented.

Although progress with criteria and methods development over just a five year time span is impressive, significant problems remain which require vigorous attack:

1. Better materials characterization, with the same concomitant theoretical development that has accompanied most of the recent materials properties collection. The test results will provide dependable properties needed as analysis input, guidance on correct failure criteria and soundly-based stress and strain limits, and support for formulation of valid constitutive relationships. Some areas especially in need of laboratory investigation are fabrication-induced residual stresses, environmentally caused time dependence of material characteristics (e.g., radiation effects, effects of carbon and nitrogen transfer by contact with hot sodium), and quantification of item-to-item differences in mechanical characteristics (e.g., lot-to-lot differences in creep behavior, properties variations caused by the precise fabrication sequence or fabrication environment of a component).

The national program coordinated by the Oak Ridge National Laboratory for Structural Design Methods for LMFBR Components is a major program which addresses many of these questions. Work under this program is being performed
at many industrial and academic sites, for example, Westinghouse Advanced Reactors and Research Division, Atomics International, Boeing, Babcock and Wilcox, the Liquid Metal-Engineering Center, Brown University, Catholic University, Penn State University, and elsewhere. Such experimental activity is vital to progress with safe and efficient design of high temperature components.

2. Refined analytic procedures to take maximum advantage of the materials characterization results. The analyst is not properly equipped at this time to validly treat such items as residual stress and time-dependent properties. Neither is he accustomed to utilizing lot or component unique properties. Hopefully, proper controls will make the latter analytic complication unnecessary, but data to date on reasonably controlled material are suggesting significant lot-to-lot differences in creep behavior, for example. Apart from the final analysis, simplified and short-cut methods are required for economic scoping calculations to provide early feedback to the designers.

3. Development of more efficient analysis methods for structural design of high temperature components. Structural design of high temperature components require a disproportionate investment in analysis. One element of increased analysis efficiency is development of both standardized and simplified methods of analysis for high temperature components. Another element is improved efficiency and increased user convenience in computer programs when multidimensional non-linear analysis cannot be avoided by simplified approaches.

4. Development of a general tool for transient fluid dynamic analysis, preferably with combined structural calculations. Until such a general tool is made available, specific needs will be met by specific programs, with little potential of the same program being applicable to future LMFBR needs or even to other needs within the same plant.

ACKNOWLEDGEMENT

The author wishes to acknowledge the useful suggestions of Mr. A.L. Snow of the Westinghouse Advanced Reactors Division on the method of presenting the structural criteria material.
### APPLICABLE STRUCTURAL CRITERIA, PREVIOUS AND CURRENT USAGE

<table>
<thead>
<tr>
<th>Edition Of ASME Boiler &amp; Pressure Vessel Code</th>
<th>ASME Elevated Temperature Code Case</th>
<th>AEC Or Contractor Supplement</th>
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<tbody>
<tr>
<td>1968</td>
<td>1331-4 (4 pp.)</td>
<td>FRA-152 (60 pp.)</td>
</tr>
<tr>
<td><strong>Minimal High Temperature Guidance</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1971</td>
<td>1331-5 (42 pp.)</td>
<td>RDT F9-1T (42 pp.)</td>
</tr>
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<td></td>
<td>1331-6</td>
<td>RDT F9-1T (42 pp.)</td>
</tr>
<tr>
<td></td>
<td>1331-7</td>
<td>RDT F9-1T (42 pp.)</td>
</tr>
<tr>
<td></td>
<td>1331-8</td>
<td>RDT F9-4T, F9-5T</td>
</tr>
<tr>
<td>1974</td>
<td>1592, 93, 94, 95 (130 pp.)</td>
<td>RDT F9-4T, F9-5T (285 pp.)</td>
</tr>
</tbody>
</table>

S6871-15

**FIGURE 1**
STRUCTURAL CRITERIA DOCUMENT TITLES


2. Interpretations Of ASME Boiler And Pressure Vessel Code, Case 1331—(4 through 8), "Nuclear Components In Elevated Temperature Service," (August 15, 1967, To December 18, 1972.)


Motivation For Developing:

To Make Better Use Of Modern Methods Of Stress Analysis By Permitting Higher Allowable Stresses Where More Detailed Knowledge Warranted Without Reduction In Pressurized Component Safety

Potential Failure Modes Considered And Related Stress Categories:

- Primary Stress Limits — Intended To Prevent Plastic Deformation And Provide Nominal Safety Factor On Ductile Burst Pressure

- Primary Plus Secondary Stress Limits — To Prevent Excessive Plastic Deformation Causing Incremental Collapse And To Validate Application Of Elastic Analysis In Fatigue Evaluation

- Peak Stress Limit — To Prevent Fatigue Failure From Cyclic Loadings

- Special Stress Limits Against Elastic And Inelastic Instability

FIGURE 3
BASIC ASME B & PV CODE, SECTION III, STRESS INTENSITY LIMITS

$S_m$ For Austenitic Steels (Not Bolting)
- $\frac{1}{3}$ Of Specified Min. Tensile Strength At Room Temp.
- $\frac{1}{3}$ Of Tensile Strength At Temp.
- $\frac{2}{3}$ Of Yield Strength At Room Temp.
- 90% Of Yield Strength At Temp.

<table>
<thead>
<tr>
<th>Stress Intensity</th>
<th>Limit</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Primary Membrane ($P_m$)</td>
<td>$S_m$</td>
<td>Design</td>
</tr>
<tr>
<td>Local Primary Membrane ($P_L$)</td>
<td>1.5 $S_m$</td>
<td>Design</td>
</tr>
<tr>
<td>Primary Membrane Plus Bending ($P_L + P_b$)</td>
<td>1.5 $S_m$</td>
<td>Design</td>
</tr>
<tr>
<td>Primary Plus Secondary ($P_L + P_b + Q$)</td>
<td>3 $S_m$</td>
<td>Normal + Upset</td>
</tr>
</tbody>
</table>

FIGURE 4
HIGHLIGHTS OF CODE CASE 1592

Bases Of Criteria:

- Sanction Design By Analysis
- Provide Failure Mode Related Limits

Unique Concerns (Related To Temperature Range Where Creep Effects Are Significant):

- Ductile Rupture From Short-Term Loadings
- Creep Rupture From Long-Term Loadings
- Creep-Fatigue Failure
- Gross Distortion Due To Incremental Collapse And Ratcheting

In General, Provides For Either Elastic Or Inelastic Analysis To Show That Strain And Creep-Fatigue Limits Are Met

S6871-13
FLOW DIAGRAM FOR ELEVATED TEMPERATURE ANALYSES

LOAD-CONTROLLED STRESS LIMITS

DESIGN CONDITIONS

USE DESIGN LOADS

Sₐ

1.5 Sₐ

PM

PL + PB

NORMAL PLUS UPSET

USE ACTUAL LOADS

Sₐt

K₁ Sₐ

1.5 Sₐm

PM

PL + PB

EMERGENCY

Σ strokes ≤ 4Sₐm

K₁ Sₐ

1.8 Sₐm

St

1.2 Sₐm

PM

PL + PB

Σ strokes ≤ 1.0

Σ U/km ≤ B

FAULTED K₁

1.2 Sₐ

1.2 Kₐ Sₐ

C₀ OR 0.9 PRL

C₀ OR 0.9 PRL

PM

PL + PB

Σ strokes ≤ 1.0

Σ U/kB ≤ 1.0

STRAIN AND DEFORMATION LIMITS

NORMAL

PLUS

UPSET

FUNCTIONAL REQUIREMENTS

LIMITS IN DESIGN SPEC

ASSUME ε = 1%

ε M = 1%

ε B = 2%

ε L = 5%

BENDING

LOCAL

CALCULATE INELASTIC STRAIN

Πₐ + Pₐ/K₁ + Oₐ

OR

ε Lifeln

CREEP-FATIGUE EVALUATION

Fig. 11

εₙ + εₜ

OR

εₙ/εₜ + P/Bₜd

DESIGN FACTORS

APPLIED F. 1

INSTAB. F. 1

BUCKLING & INSTABILITY

NO LIMITS

UNLESS SPECIFIED

IN THE DESIGN SPECIFICATION

LEGEND

CONTROLLED QUANTITY
FOR ELASTIC ANALYSIS

CONTROLLED QUANTITY
FOR INELASTIC ANALYSIS

COMPUTED QUANTITY

FIGURE 6
CLASS 1 VALVE WALL THICKNESS REQUIREMENT

\[ t_m \geq \frac{1.5 P d_m}{2S_o - 2P(1-y)} + 0.1 \]

- \( t_m \) = MINIMUM PRESSURE WALL THICKNESS (in.)
- \( P \) = Design Pressure At Design Temp.
- \( d_m \) = Larger Inside Diameter Near Weld End (in.)
- \( S_o \) = Allowable Stress At Design Temp.
- \( y \) = Plastic Stress Distribution Factor

<table>
<thead>
<tr>
<th>Design Temp. (°F)</th>
<th>( y ) (Ferritic Steels)</th>
<th>( y ) (Austenitic Steels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \leq 900 )</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>( 950 )</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>( 1000 )</td>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
<td>( 1050 )</td>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
<td>( 1100 )</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td>( \geq 1150 )</td>
<td>0.7</td>
<td>0.7</td>
</tr>
</tbody>
</table>

REF. 1592.—3513
USER INDEPENDENT RESPONSIBILITIES
IN HIGH TEMPERATURE ANALYSIS

User Is Responsible For:

- Accounting For Environmental Deterioration Of Material (Corrosion Mass Transfer, Radiation Effects, Sensitization, Etc.) (1592, - 1110 (e))
- Functional Performance-Related Deformation (1592, - 1110 (e))
- Calculational Method And Mathematical Formulation Of Multiaxial Plastic Flow Behavior (1592, - 3212 (b) And - 3214.2)
- Calculational Method And Mathematical Formulation Of Creep Behavior And Creep-Fatigue Interaction (1592, - 3214.2)
- Evaluation Of Buckling Including Creep Collapse (1592, - 3213.21 And - 3213.22)
- Definition Of Alternate Strain, Deformation, And Fatigue Limits, If Appropriate (1592, - 3252)
PURPOSE AND CONTENT
RDT STRUCTURAL STANDARD F9-4T

Title—“Requirements For Design Of Nuclear System Components At Elevated Temperatures (Supplement To ASME Code Case 1331)” (13 pp).

Purpose—To Selectively Add Conservatism To ASME High Temperature Criteria Where Judged Necessary.

Key Provisions

• Manufacturer Preparation Of A Structural Evaluation Plan
• More Detailed Treatment Of Environmental Effects
• More Conservative Treatment Of Allowable Time At Primary Membrane Plus Bending Load ($t_{ib}$)
• More Conservative Primary Membrane Plus Bending Limit Dependent On Specific Component Geometry ($P_L + P_b$) ≤ 1.5 $S_m$ Or $K_{St}$)

FIGURE 9
PURPOSE AND CONTENT,
RDT STRUCTURAL STANDARD F9-5T

Title—“Guidelines And Procedures For Design Of Nuclear System Components At Elevated Temperatures” (273 PP., Non-Mandatory)

Purpose—To Assist User (In A Document Largely Prepared By Users) In Understanding, Interpreting, And Using High Temperature Code Criteria

Content
• Structural Evaluation Program
• Sequence Of Analysis
• Inelastic Analysis Methods (E.G., Stress-Strain Relationships, Plastic And Creep Hardening, Plastic And Creep Flow Direction)
• Verification And Qualification Of Analytic Methods
• Evaluation Of Results Against Limits
• Fabrication And Environmental Effects
• High Temperature Material Behavior
STRUCTURAL ANALYSIS COMPUTER PROGRAMS
SUITABLE FOR VALVE ANALYSIS

1. Name—MARC Series
   Source—MARC Analysis Research Corp., Providence, Rhode Island.

2. Name—ANSYS
   Source—Swanson Analysis Systems, Inc., Elizabeth, Pennsylvania

3. Name—Creep-Plast
   Source—(Developed By General Electric Under Subcontract To Oak Ridge National Laboratory) ORNL, Oak Ridge, Tennessee.
4. Name—EPACA

*Source*—(Developed By Franklin Institute Under Subcontract To Oak Ridge National Laboratory) ORNL, Oak Ridge, Tennessee.


5. Name—Foster Wheeler Program R-1045

*Source*—Foster Wheeler Corporation, Livingston, New Jersey.


6. Basic Technology Program BT1511


REDUCED THREE DIMENSIONAL MODEL, 28- INCH HOT LEG ISOLATION VALVE

FIGURE 12
FINITE ELEMENT MODEL,
28-INCH HOT LEG ISOLATION VALVE GATE

FIGURE 13
COMPUTER PLOTTED DISPLACEMENTS
AND STREW INTENSITY DISTRIBUTION,
28-INCH HOT LEG ISOLATION VALVE GATE

FIGURE 14
BODY GEOMETRY, 4-INCH ISOLATION/FLOW CONTROL VALVE

FIGURE 16
MIDPLANE MEMBRANE STREW DISTRIBUTION,
375 PSI INTERNAL PRESSURE,
4-INCH ISOLATION/FLOW CONTROL VALVE

FIGURE 18
DACVA—FLUID DYNAMIC COMPUTER PROGRAM
FOR FAST FLUX TEST FACILITY CHECK VALVE ANALYSIS

Source—Formulated By Rockwell Manufacturing Company,
Modified By O'Donnell & Associates, Inc.

Purpose—To Perform Fluid Dynamic Transient Analysis Of The Fast Flux
Test Facility (FFTF) Primary Loop Check Valves.

Required Input Data—
- Dashpot And Valve Disc Geometry
- Dashpot Equation
- Friction Data
- Fluid Properties (Including Bulk Modulus)
- Masses And Moments Of Inertia
- Primary Loop Component Volumes And Fluid Impedances

Output—
- Disc Location, Velocity, And Acceleration
- Dashpot Piston Location
- Pressure History On Both Sides Of Disc
PRIMARY SYSTEM 16-INCH COLD LEG CHECK VALVE

VENT & MAINTENANCE OPENING

FREE STANDING SEAT

DASHPOT

INLET

SWING DISC

OUTLET

FIGURE 20
SAMPLE DACVA RESULTS

2 LOOPS START AT TIME=0
3RD LOOP STARTS AT TIME=60 SEC
3RD LOOP FAILS AT DISK ANGLE OF 10°

DISK ON STOP AT 13 SEC. WITH IMPACT VELOCITY OF 0.11 RAD/SEC.

DASHPOT ENGAGED AT 5.0 SEC. WITH AN IMPACT VELOCITY OF -.83 RAD/SEC. DISK ANGLE = 4.2

PUMP FAILS

CHECK VALVE CLOSES AT 13.79 SEC. WITH A SURGE OF 12 PSI

PUMP STARTS

DASHPOT ENGAGED AT 88.1 SEC. WITH AN IMPACT VELOCITY OF -.88 RAD/SEC. DISK ANGLE = 0.9

CHECK VALVE CLOSES AT 93.1 SEC. WITH A SURGE OF 0.77 PSI

CHECK VALVE ABOUT TO OPEN AT 54.9 SEC.

FIGURE 27
SODIUM VALVE MANUFACTURING DEVELOPMENT

For Presentation at International Specialists Meeting on "Operating Experience and Design Criteria of Sodium Valves", Sponsored by the International Working Group on Fast Reactors of the International Atomic Energy Agency.

Hanford Engineering Development Laboratory Richland, Washington

September 23-27, 1974

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1.0 INTRODUCTION
The purpose of this paper is to review some items of special interest from recent USA experience with the manufacture of sodium valves. The items to be discussed are:

1. Valve forging fabrication
2. Welding processes
3. Hardfacing processes
4. Multi-dimensional machining
5. Bellows fabrication

2.0 VALVE FORGING FABRICATION
Current sodium valve bodies have tended to be constructed of forgings rather than castings, the more traditional valve body construction. Two reasons for using forgings are the less uniform material quality of castings and the difficulty, because of metallurgical structure, of performing volumetric inspections of castings. Figure 1 is a picture of the completed Fast Flux Test Facility (FFTF) primary loop 16-inch check valve, one of the large valves discussed earlier by Mr. Nulton. The body is simply a weldment of joined 304 stainless steel forgings. Some of the forgings intended for use in the FFTF primary valves were found to have large grain size and to have an uneven distribution of grain size. Figure 2 is a metallograph of a forging intended for use in the FFTF check valve body but rejected because of coarse, uneven internal structure. Figure 3 shows the variation of grain size with azimuthal location. The first indication of large grain size in these forgings was inability to perform meaningful ultrasonic inspection of the forging in the 1.0 to 5.0 MHZ range, as required. That is, grain boundaries produced "hash" in the ultrasonic reflection signal, reacting to the sound waves like multiple internal material defects. Now it is well known that large grain size actually improves some high temperature mechanical properties. However, in the balance, fine and even grain structure is preferred, for good, uniform, isotropic structural material. Figure 4 summarizes the forging grain size problem. The cause is clearly fabrication process related. The recommended solutions involve careful process planning and monitored implementation, as well as attention to minimizing as-forged cross section within economic practicality. Grain size generally increases with increasing
distance from the forging die. Better understanding of grain size effects on properties and of process parameters on grain size will support more intelligent forging fabrication planning. A second forging problem which had serious cost and schedule consequences during the course of FFTF primary valve fabrication was a poor weldability situation. A full explanation for this problem is still being pursued. Bar forgings (approximately 8 inches by 10 inches in cross section) which were intended for use as beams for the FFTF primary hot leg isolation valves gave an early signal of trouble by having a grain structure which interfered with performance of the specified ultrasonic inspections. However, the material was initially accepted based on supplementary inspections, principally metallurgical examination, mechanical strength tests, and radiographic examination. A second sign of trouble was fissuring in Stellite hardfacing which was applied to selected areas of the machined beam. The hardface fissuring was eliminated by depositing a sublayer of 308 stainless steel between the beam base material and the hardfacing. However, in the heat affected zone on the edges of the 308 deposits and at the 308-base material interface, occurrence of small fissures or "hot tearing" was observed in the base material. With this indication of unacceptable weldability, the material was replaced. This experience is summarized on Figure 5. It is seen that better understanding of this incident is called for (and, in fact, samples of the beam are now at Oak Ridge National Laboratory for further testing) and that weldability tests are recommended under certain circumstances.

3.0 WELDING PROCESSES
As can be expected with valves that have large overall dimensions with small wall thickness, that have stringent leakage requirements, or that fit both descriptions, welding distortion is a matter which requires special consideration during the course of fabrication. As an example, the FFTF hot leg isolation valves have a maximum diameter of 54 inches while the wall thickness is about 0.9 inch. During the course of primary valve manufacture in the Foster Wheeler Corporation shops, the extent of welding distortion was not initially anticipated and valve manufacture had to be interrupted while additional fixturing was designed and built to bring parts into proper align-
ment for the next step in the assembly of the total weldment.

The design of the FFTF primary valves is such that the seats are mechanically isolated (by flexibility of connecting parts) from the valve body. In that way, the seats are largely protected from the influence of changes in valve body shape due to thermal and mechanical service loads as well as from weld distortion (or inservice relief of residual welding stresses). To minimize welding and hardfacing-induced distortion within the seat assembly itself, this part of the valve was heat treated at a moderate temperature before final machining. However, the external body structures are not heat treated out of a concern that such heat treatment will sensitize the 304 or 316 stainless steel material and make it susceptible to intergranular corrosion by the post-heat treatment environment (fabrication, storage, plant erection, and plant operation atmospheres). The FFTF isolation valves have been successfully assembled with sound welds and seat leakage has been measured to be about 10% of the specified maximum. However, two improvements in manufacture suggest themselves. First, in-process welding distortion should be realistically anticipated and necessary fixturing built to insure good part alignment during welding. Secondly, the advisability of high temperature heat treatment of all austenitic stainless steel weldments should continue to be studied for a good compromise between dimensional stability and risk of sensitization. On the design side, the distortion problem could be reduced by insuring that only essential hardfacing is applied.

The Valcor sodium valves, which operate on a floating seal bar principle as described in Dr. McGough's presentation, require an optical flatness at the seat-disc interface and therefore are particularly sensitive to distortions arising out of welding processes. The solution for this design was the use of electron beam structural welds, a low heat input welding process. As was discussed by Dr. McGough, the weld porosity at the edge of the electron beam makes good volumetric inspection (radiography or ultrasonics) very difficult in the design as it stands and conformance with Code limits problematic. This welding process is now considered adequate for the intended purpose. A recent ASME Code ruling (providing for additional local wall thickness in which the electron beam can terminate and where the inherent
Future applications should make volumetric inspection more convenient and dependable by prior planning in the design and placement of the valve welds.

4.0 HARDFACING PROCESSES

Related to the more general subject of welding is hardfacing. Special wear areas on the sodium valves have been handled both by use of cast Stellite or solid Inconel 718 pieces as well as by weld process deposition of Stellite. Three weld processes have been used for Stellite hardfacing, plasma transfer arc (PTA) (not a spraying process but one in which the current path is actually from the base material through the plasma stream), tungsten inert gas (TIG), and oxyacetylene torch welding. The discussion will focus on welded deposition of Stellite by PTA and TIG. The oxyacetylene process can produce very high quality hardfacing in the hands of a highly skilled welder but the quality of the process is too welder-dependent to have been used widely, especially on large areas of deposition. The process parameters in use on the recently fabricated sodium valves are summarized on Figure 6. It is important to understand that the temperature ranges shown are not within a given welding process procedure but a range among the processes as applied by the various sodium valve manufacturers (data from Crane Company, Foster Wheeler Corporation, and Sargent Industries). One aspect of the hardfacing which has created a special challenge for the manufacturers is the maximum iron content at the surface of the hardface deposit. A limited amount of data associates poor anti-galling properties with the presence of significant iron content in the Stellite hardfacing. Whether the 6% limit is essential is not justified, but there is fairly general agreement that the limit should not be greater than 12%. Nevertheless, the current requirement remains 6%. Response to the requirement takes the form of three process influences. First, iron diffusion from the stainless steel parent material into the hardfacing is reduced, as expected, by lowering preheat and interpass temperatures. However, some compromise is required since higher temperatures favor a better fusion bond between hardfacing and substrate. Secondly, iron content in the Stellite material for the deposition processes is controlled. Thirdly, the hardfacing, especially in PTA deposition, is best laid in a material groove. However, iron diffusion across the
lateral (groove edge) hardface-substrate interface increases the iron diffusing into the hardface surface. This problem is corrected by machining away the lateral interfaces. Figure 7 shows the geometry of the hardfacing qualification mockup for the seat hardfacing of the FFTF primary-check valve. The hardface deposit as it exists immediately after the PTA-process is shown as well as the finish machined shape of the hardface. It can be seen that the portion of the deposit which is influenced by lateral iron diffusion is simply machined away.

5.0 MULTI-DIMENSIONAL MACHINING

Brief comments will be made here on problems encountered in three dimensional machining. A case in point is the FFTF primary isolation valve hillside penetrations. Figure 8 will refresh your memory on the nature of this complicated three-dimensional shape. It is through this penetration that the valve operator shafting passes through the valve body. Design of the penetration was difficult since competing demands of valve internal pressure loads (favoring a small diameter and thick wall), transient thermal shock loads (favoring thin walls), and lateral seismic loads as imposed by the operator components (favoring a large diameter) had all to be met. The complex dome shape as shown resulted. Great difficulty was encountered in completing the three dimensional machining with precision, not to mention the difficulty of simply inspecting the pieces for conformance to the engineering drawings. The discrepancies are being corrected with painstaking manual grinding of the machined parts and this kind of machining error could eventually require weld overlay repair followed by grinding. Because of the manufacturing difficulty of producing odd configurations, structural design and analysis effort should devote maximum attention to meeting functional and structural adequacy needs with simpler shapes. If complexity must be there, the machining difficulty can be reduced considerably if the part is forged as close to final shape as possible, potentially requiring no machining except weld preparations and precisely located surfaces. Careful selection of equipment (or subcontractor) and a well thought out inspection procedure will also be helpful. Economics will favor forging to shape, of course, only if a significant number of the same shape component are required.
6.0 BELLOWS FABRICATION

I will summarize Dr. McGough's earlier comments on bellows seal fabrication—
for small sodium valves. The objective is simply to bring the subject into
the context of major manufacturing development achievements in sodium valve
design and manufacture. As was reported earlier, the small valves now have
three ply bellows without longitudinal seams. Two plies are of Inconel 718
and the third, in contact with the sodium, is 316 stainless steel. Three
concentric drawn tubes (of 0.005 to 0.008 in. wall thickness) are formed into
the bellows convolution shape. After forming, the ply ends are sealed by
resistance welding. Early bellows failed in testing due to problems with
wall thickness uniformity, fatigue failure apparently precipitated by grain
boundary attack, and uneven forming. However, the current bellows design
has been shown by testing to be quite suitable for the small valve primary
seal application. One anticipated improvement is the use of Inconel 718 for
all three layers, presuming that increased data on Inconel 718 in a sodium
environment establishes good materials compatibility.

7.0 SUMMARY AND CONCLUSIONS

Selected areas of recent sodium valve manufacture which required development
were discussed. In each case, the development progressed to the point of
providing high quality valves which are expected to provide reliable sodium
service. There are several areas where additional development work would
be fruitful.

The following are suggested as activities which have a potential of improving
the manufacturability and/or quality of sodium valves:

1. Better understanding of the forging process temperature effects and careful
balancing of ideal forging practice with economic considerations. The next
step is implementation in the forging shops with adequate monitoring for con-
formance with the process specification.

2. Judicious application of solution annealing before final machining of
valves or valve subassemblies requiring precise dimensional stability. Sol-
ution annealing with a rapid quench does not produce sensitization.
3. Better weld joint design and placement in those instances where electron beam welding best meets the individual-valve needs, as in the Valcor small-valve design. Improved design foresight should better accommodate the peculiarities of electron beam welding and the problems of volumetric examination.

4. Consideration of a more liberal iron content in hardfacing so that interpass temperatures can be raised to improve fusion without leading to truly harmful levels of iron.

5. Development of alternate hardfacing materials and processes for austenitic stainless steel valve parts (and potentially for Inconel valve parts). Two characteristics to be sought are better thermal expansion compatibility between the hardface material and the substrate and hardfacing alloys with little or no cobalt.

6. Maximum simplicity in valve design. Difficulties encountered during fabrication of sodium valves of recent vintage again demonstrated the importance of this old engineering principle. In addition to design effort to meet requirements with the simplest configuration, system designers should strike a better compromise between the stringency of requirements and what is attainable with a practical design.
PHOTO OF COMPLETED FFTF
16-INCH CHECK VALVE
(NOT AVAILABLE AT THIS TIME)

FIGURE 1
CYLINDRICAL FORGING CROSS SECTION
(LARGE GRAIN SIZE)
CYLINDRICAL FORGING CROSS SECTION
(UNEVEN GRAIN SIZE)
FORGING QUALITY EXPERIENCE—
LARGE, UNEVEN GRAIN SIZE

**Problem**—Certain Forgings Showed Large And/Or Uneven Grain Size, Interfering With Meaningful Ultrasonic Inspection And Potentially Causing Anisotropic Behavior.

**Cause/Contributing Factors**—
- Large Forging Cross Section
- Process Parameters, Especially Temperature History During Process

**Recommended Solution**—
- Specify “Fine Grain Practice” And More Closely Monitor Forging Process Plan And Execution
- Forge To Final Shape As Far As Economically Advisable
- Depend On Successful Ultrasonic Inspection As Indicating Acceptable Grain Size Unless Number Of Identical Forgings Justifies Destructive Examination

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FIGURE 4
FORGING QUALITY EXPERIENCE—WELDABILITY

Problem—Bar Forging Showed Poor Weldability (Hot Tearing In Heat Affected Zone) And Grain Size Too Large To Permit Meaningful Ultrasonic Inspection (1.0 To 5.0 MHZ Specified)

Causes/Contributing Factors—
  • Trace Element Chemical Contamination (Suspected Cause)
  • Large-Grain-Related Process Parameter (Suspected Contributing Factor)

Recommended Solution—
  • Additional Tests And Examinations Of Material (Underway At Oak Ridge National Laboratory)
  • Weldability Tests Of Forgings With Large Grain Size

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FIGURE 5
# TYPICAL STELLITE
## HARD FACING PROCESS PARAMETERS

<table>
<thead>
<tr>
<th>Application</th>
<th>Plasma Transfer Arc (PTA)</th>
<th>Tungsten Inert Gas (TIG)</th>
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</thead>
<tbody>
<tr>
<td>Hardfacing Material</td>
<td>Stellite 156 Powder</td>
<td>Stellite 6 Rod</td>
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<tr>
<td>Shielding Gas</td>
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<td>Argon</td>
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<tr>
<td>Powder Carrier Gas</td>
<td>Helium</td>
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<td>300-800</td>
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<tr>
<td>Max. Interpass Temp. (°F)</td>
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<td>Max. Iron Content</td>
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<td>6%</td>
</tr>
<tr>
<td>Min. Surface Hardness (Rockwell C)</td>
<td>38</td>
<td>38</td>
</tr>
</tbody>
</table>

**FIGURE 6**

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16-INCH CHECK, VALVE SEAT HARDFACING AS DEPOSITED AND A FINAL MACHINED

FIGURE 7