Letter Report

**Defense Waste Processing Facility Pour Spout
Heaters – Conceptual Designs and Modeling**

**Tanks Focus Area
RL3-7-WT-31 (Task A)**

S. K. Sundaram and J. M. Perez, Jr.
Pacific Northwest National Laboratory^a, Richland, WA 99352

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Summary

The Tanks Focus Area (TFA) identified a major task to address performance limitations and deficiencies of the Defense Waste Processing Facility (DWPF) now in its sixth year of operation. Design, installation, testing, monitoring, operability, and a number of other characteristics were studied by research personnel collaboratively at a number of facilities: Savannah River Technology Center (SRTC), Clemson Environmental Technologies Laboratory (CETL), Pacific Northwest National Laboratory (PNNL), and the Idaho National Engineering and Environmental Laboratory (INEEL). Because the potential limiting feature to the DWPF was identified as the pour spout/riser heater, researches on alternative design concepts originally proposed in the past were revisited. In the original works, finite element modeling was performed to evaluate temperature distribution and stress of the design currently used at the DWPF. Studies were also made to define the requirements of the design and to consider the approaches for remote removal/replacement. Their heater type/location, their remotely replaceable thermocouples, and their capabilities for remote handling characterized the five alternative designs proposed. Review comments on the alternative designs indicated a relatively wide range of advantages and disadvantages of the designs. The present report provides an overview of the design criteria, modeling results, and alternative designs. Based on a review of the past design optimization activities and an assessment of recent experience, recommendations are proposed for future consideration and improvement.

Acronyms and Abbreviations

CETL	Clemson Environmental Technology Laboratory
DWPF	Defense Waste Processing Facility
FH	Fluor Hanford
HAW	High Activity Glass
HWVP	Hanford Waste Vitrification Plant
INEEL	Idaho National Engineering and Environmental Laboratory
KfK	Kernforschungszentrum Karlsruhe
PNNL	Pacific Northwest National Laboratory
SRTC	Savannah River Technology Center
SSC	Swanson Service Corporation
TBS	To Be Supplied
TFA	Tanks Focus Area
TIM	Technology Integration Manager
TTP	Technical Task Plan
WSRC	Westinghouse Savannah River Company
WVDP	West Valley Demonstration Project

Acknowledgments

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1. Introduction

The melter technology within the Defense Waste Processing Facility (DWPF) was designed over 15 years ago; was operated non-radioactively for two years followed by four years of radioactive operations. To date, over 830 canisters of immobilized high-level waste totaling over three million pounds of glass have been produced by a single melter unit. During the first two years of radioactive operation, several areas for improvement in melter design were identified. The facility and equipment were sized and designed based on continuous melter operation. Therefore, down time associated with disruptions to melter operation and glass pouring have significant schedule and cost impacts. A major task was initiated to address performance limitations and deficiencies identified by the user, DWPF, under the Tanks Focus Area (TFA) Program. This work is being performed in collaboration with Task Technical Plans (TTP) SR16WT31-C, RL37WT31-A and C (FY 1999-2000 TTP), and ID77WT31-B. The site tasks planned to improve the feed melter chemistry, improve melt rate, reduce corrosion, and reduce foaming as demonstrated in a melter. The glass chemistry work in the TFA Task 98059 was integrated with this task to ensure materials compatibility and to define performance requirements. The results of these tasks will also be application to vitrification of High Activity Waste (HAW) at the Idaho National Engineering and Environmental Laboratory (INEEL).

A comprehensive test program is being performed with the objective of improving operability issues by evaluating alternative critical component design (TFA Technology Abstract 2000). Additionally, a joint SRTC - Pacific Northwest National Laboratory (PNNL) team evaluated commercially available melter designs (national and international) for application in the DWPF and at Idaho (Sundaram et al. 1999). Under this task, a full DWPF-size stirred test melter, and related test components were installed and tested at the Clemson University Environmental Technologies Laboratory (CETL) with Westinghouse Savannah River Company (WSRC) staff oversight and collaboration. The task installed, tested, and operated the melter, including design, construction, and operation of a full scale simulated DWPF riser and pour spout. During FY99, Savannah River Technology Center (SRTC) and Clemson University continued testing melter pour spout improvements. Operational and functional testing of the stirring feature of the melter required to achieve high pour rates for pour spout design tests were conducted.

During FY 00, PNNL task scope includes evaluating pour spout heater analyses previously performed by the Hanford Waste Vitrification Plant (HWVP) Project. This report summarizes the design criteria, modeling results, and alternative designs that were completed by the HWVP project.

2. Modeling

The HWVP conducted engineering studies to evaluate the feasibility of adapting the DWPF riser/pour spout heater design for remote maintenance and replacement. These melter components were originally designed to meet melter service life requirements (two years). As such, they are not replaceable and only minimal maintenance is possible. A design acceptability study of the riser/pour spout heater was conducted for HWVP by Swanson Service Corporation (SSC) for Fluor Daniel Inc. (FDI) (Malcolm 1993). The main criteria considered for the design acceptance were:

1. Glass waste product within the riser tube must not fall below 1049°C (1925°F), precluding the formation of spinels.
2. Inconel™ dam must not exceed 732°C (1350°F) to prevent glass flow into the riser/overflow heater chamber.
3. Silicon carbide heaters must operate at reasonable temperatures to allow an adequate life span.

The design was analyzed using the ANSYS finite element computer program (Revision 4.4A). ANSYS is a peer-respected and well-accepted program throughout the commercial and defense industries, and uses quality procedures according to those of the U.S. Nuclear Regulatory Commission. The pour spout portion of the riser/pour spout assembly was modeled separately from the riser in an effort to reduce the overall model size. As the pour spout was located a significant distance from the Inconel dam area and would, therefore, have a minimal effect on its temperature, this approach was reasonable. The pour spout model consists of 19,448 finite elements (ANSYS - STIF70 Appendix A). The model is shown in Figures 1 through 4.

The entire heating chamber (where the heaters normally reside) is expected to be at an elevated temperature (necessary to keep the glass molten). Therefore, it was reasonably assumed the predominant form of heat transfer in the chamber would be radiation. The ANSYS radiation substructure utility (Appendix B) was used to model this type of heat transfer within a complex geometry. The utility allowed for automatic calculation of view factors based on gray body diffuse radiation using a hidden face algorithm. The basic procedure required the superposition of shell elements onto all solid model faces that are to be considered for radiation. The data of these elements (node location and element connectivity) were input to the radiation substructure generation utility (AUX12) that calculated a form factor from each element to every other element. These form factors were then used as "super-elements" in the thermal analysis. Figure 5 shows shells as generated for the chamber geometry. The emissivity values were varied over 0.6-0.9 for Inconel and 0.3-0.6 for the insulation. Note the color legend in Figure 6 is applicable to Figures 1 through 5.

A summary of materials and their conductivity, as used in these analyses, is shown in Table 1. For the purpose of these analyses, not all material properties were considered to be dependent on temperature. Inclusion of the nonlinear effect of temperature-dependent material properties to the already nonlinear analysis (due to radiation) resulted in a highly nonlinear system that required significant computer time for solution. Therefore, temperature-dependent material properties were specified only for those materials that were subject to extreme temperature ranges. Remaining material properties were input as constant values, based upon prior data and an assumed final temperature.

Boundary conditions were dictated by the appropriate contacting heating or cooling fluid. Initially, the internal surfaces of the melter were assumed to be the temperature of the molten glass, 1093°C (2000°F). The external surfaces of the riser (with the exception of the top surface of the replaceable heater unit), the melter cylinder shell, and the melter bottoms were assumed to be the average temperature of the cooling water (115°F). The top of the replaceable heater has no cooling jacket and was assumed to cool by natural convection ($H = 1.9 \text{ BTU/Hr ft}^2 \text{ }^\circ\text{F}$) to an ambient temperature of 104°F. Heating of the riser chamber was accomplished by plate type heating elements that lined the bottom of the removable portion of the riser and the ceiling of the heating chamber. The heat generation of each plate varied depending upon its location in the riser. The relative heat-generation rates of the heaters included in the model would have a significant effect on the temperature distribution of the glass in the riser tube. The heat generation from the radioactive decay of the glass was neglected for simplicity.

The ANSYS program utilized an iterative looping solution technique for these highly nonlinear analyses. This technique required the program to assume a starting temperature state from which it could calculate the nonlinear parameters (conductivity and heat flow due to radiation) of the problem. The program was instructed to terminate the looping procedure when two successive cycles changed by less than the specified convergence criteria value of 5°F. The results were presented in the form of colored graphical plots of temperature distributions and temperatures along paths of interest. The materials legend is shown in Figure 6. The results of the pour spout heater analysis are presented in Figures 7 – 11. These results indicate the design configuration is capable of meeting the specified thermal requirements and criteria.

ANSYS 4.4A
MAR 2 1993
9:29:34
PLOT NO. 1
POST1 ELEMENTS
MAT NUM

XV =1
YV =1
ZV =1
*DIST=30
XF =79.336
YF =54.521
ZF =0.5
PRECISE HIDDEN

Figure 1. Pour Spout Heater Finite Element Model – Isometric View

ANSYS 4.4A
MAR 2 1993
9:34:16
PLOT NO. 2
POST1 ELEMENTS
MAT NUM

XV =1
YV =1
ZV =1
*DIST=30
*XF =79.336
*YF =54.521
*ZF =-6
PRECISE HIDDEN

Figure 2. Pour Spout Heater Finite Element Model – Cross Section

ANSYS 4.4A
MAR 2 1993
9:24:42
PLOT NO. 1
POST1 ELEMENTS

XV =1
*DIST=20
*XF =60
*YF =50
SECTION

Figure 3. Pour Spout Heater Finite Element Model – Riser Section

ANSYS 4.4A
MAR 2 1993
9:02:04
PLOT NO. 1
POST1 ELEMENTS

XV =1
DIST=25.58
*XF =97
*YF =54.5
SECTION

Figure 4. Pour Spout Heater Finite Element Model – Pour Spout Section

7

```
ANSYS  4.4A
MAR 29 1993
17:07:15
PREP7 ELEMENTS
MAT  NUM
```

```
XV  =1
YV  =1
ZV  =1
DIST=17.639
XF  =74.007
YF  =56.662
ZF  =-2.15
PRECISE HIDDEN
```

Figure 5. Radiative Surface Elements – Riser Heater Mode

	K3/Melter Tank
	DSM-24/Melter Tank
	ZIRMUL/Melter Tank Bottom
	FIBERFAX T30/Tank Bottom
	ZIRCAR ZAL-15/Riser
	ZIRCAR AL-30/Riser
	INCONEL/Dam
	INCONEL 690/Riser Tube
	Silicon Carbide/Heater
	Glass Product/Riser Tube
	ZIRCAR RS-100/Outer Edge of Inconel Dam
	304 Stainless Steel/Riser Outer Shell

Figure 6. Materials Color Legend for Element Plots (Applicable to Figures 1-5)

Table 1. Summary of Material Properties

<u>MATERIAL</u>		<u>PROPERTY</u>			
NO	DESCRIPTION	TEMP (° F)	K $\left(\frac{BTU \cdot IN}{HR \cdot IN^2 \cdot ^\circ F} \right)$	DENSITY LB/IN ³	C BTU/LB° F
1	K3/MELTER TANK	1500	.1563	.138	.25
2	DSM-24/MELTER TANK	-	.00611	.023	.27
3	ZIRMUL/MELTER TANK BOTTOM	1500	.0888	.106	.28
4	FIBERFAX T-30/MELTER TANK BOTTOM	-	.004583	.028	.27
5	ZIRCAR ZAL-15/RISER			.0087	.25
6	ZIRCAR AL-30/RISER			.0174	.25
7	INCONEL/DAM/RISER TUBE			.296	.107
11	SILICON CARBIDE HEATER	-	.833	.098	.435
12	GLASS PRODUCT	2000	.2123	.089	.362
13	ZIRCAR RS-100			.075	.28
18	304 STAINLESS OUTER SHELL	700	.983	.282	.11

ANSYS 4.4A
 MAR 2 1993
 8:27:32
 PLOT NO. 1
 POST1 STRESS
 STEP=2
 ITER=10
 TEMP
 SMN =115
 SMX =2135

XV =1
 YV =1
 ZV =1
 *DIST=30
 *XF =75.954
 *YF =52.465
 *ZF =-0.562026

PRECISE HIDDEN
 115
 339.474
 563.947
 788.421
 1013
 1237
 1462
 1686
 1911
 2135

Figure 7. Pour Spout Temperature Distribution

ANSYS 4.4A
 MAR 2 1993
 8:44:15
 PLOT NO. 1
 POST1 STRESS
 STEP=2
 ITER=10
 TEMP
 SMN =115
 SMX =5954

XV =1
 DIST=25.557
 XF =79.336
 YF =54.521
 ZF =0.5
 SECTION

■	-275
■	0
■	275
■	550
■	825
■	1100
■	1375
■	1650
■	1925
■	2200

Figure 8. Pour Spout Temperature Distribution – Riser Section

Figure 9. Pour Spout Temperature Distribution – Spout Section

ANSYS 4.4A
MAR 2 1993
8:56:17
PLOT NO. 1
POST1 STRESS

ITER=10
TEMP
SMN =115
SMX =5954

XV =1
DIST=25.58
*XF =97
*YF =54.5

SECTION
115
763.823
1413
2061
2710
3359
4008
4657
5306
5954

Figure 10. Pour Spout Temperature Distribution – Second Run

FLUOR MELTER POUR SPOUT - QE = 35 & 50

ANSYS 4.4A
 MAR 2 1993
 8:11:35
 PLOT NO. 1
 POST1
 STEP=2
 ITER=10
 PATH PLOT
 NOD1=15866
 NOD2=16507
 TEMP

ZV =1
 DIST=0.6666
 XF =0.5
 YF =0.5
 ZF =0.5

Figure 11. Pour Spout Glass Centerline Temperature

3. Alternative Design Concepts

As part of HWVP activities to adopt DWPF technology, a potential limiting feature to the service life of the DWPF melter was identified as the pour spout/riser heater section. An engineering study was undertaken in 1990 (DOE Contract DE-AC06-86RL10838, 1990) to develop and evaluate alternative design concepts that would improve the overall service life of the melter. The study produced five alternative design concepts to the existing design. The study included sketches, narrative descriptions, and calculations to support evaluations. A summary of this study is presented in this section.

The alternative design concepts must meet the following requirements:

1. The glass temperature in the riser and pour spout must be maintained at a minimum of 1049°C (1920°F) to achieve low glass viscosity and proper flow conditions.
2. The vacuum supported glass pour system must be capable of filling the canisters.
3. The nominal outside shell temperature of the pour spout/riser section shall not exceed 50°C (122°F); localized higher outside temperatures are allowed.
4. Penetration of glass to the remotely replaceable components and the melter shell must be prevented to avoid an electrical short circuit to the melt pool.
5. The lifetime of the components that are not removable must be a minimum of four years.

The following approaches were considered for remote removal/replacement of the heaters:

- a) A vertical lift removal/replacement approach, as adapted by the West Valley Demonstration Project (WVDP) melter
- b) A removal/replacement approach based on use of special tools and fixtures, such as those required to remove/replace remotely exchangeable piping penetrations in the HWVP canyon cells
- c) A removal/replacement approach based on the use of special extended reach tools that allow the use of remote connections in normally inaccessible locations and that support combined horizontal/vertical motion removal/replacement schemes

The alternative configurations were characterized by: a) heater type and location, b) remotely replaceable thermocouples and location, and c) tools and orientation of movements for remote handling. The characteristics of the five designs are summarized in Table 2. The evaluation criteria and preselection of the alternative designs are summarized in Table 3. Experts in the field reviewed the designs¹. The comments are summarized in Table 4.

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¹ Private communications from Gary Sevigny (PNNL), K. R. Routt (WVDP), and D. C. Iverson (DWPF). 1990.

Table 2. Characteristics of Alternative Design Concepts

Heater	Thermocouple	Remote Handling
Alternative Design A (Figures 12a and 12b) - Vertically mounted heating assemblies, one for the riser section and one for the pour spout section - Double spiral SiC or U-shaped metallic or U-shaped MoSi₂	- Two pairs (remotely replaceable) vertically inserted into the riser heater assembly - Two horizontally inserted into pour spout section	- Melter cell crane or canyon crane - Remote connections opened or closed with the impact wrench attached to one of the cranes - Straight vertical lift for positioning and replacement of the heater assembly - Two guide pins to position the assembly properly
Alternative Design B (Figures 13a and 13b) - Vertically mounted heating assemblies, one for the riser section and one for the pour spout section - Double spiral SiC or U-shaped metallic or U-shaped MoSi₂	- Two pairs (remotely replaceable) vertically inserted into the riser heater assembly - Two horizontally inserted into pour spout section	- Melter cell crane or canyon crane - Remote connections opened or closed with the impact wrench attached to one of the cranes - Straight vertical lift for positioning and replacement of the heater assembly - Guide pins to position the assembly properly
Alternative Design C (Figures 14a and 14b) - A hood assembly with horizontally mounted heating elements for the riser section - An assembly with horizontally mounted heating elements for the pour spout section - Double spiral SiC or U-shaped metallic or U-shaped MoSi₂	- Four thermocouples in the riser hood assembly (separately replaceable, if practical) - Two thermocouples in the pour spout assembly (not separately replaceable)	The riser hood assembly - Pre-positioned by combining vertical and horizontal movements using the melter cell crane or the canyon crane - A fixture with guide pins mounted on the assembly that slide into counterpart guides located on the melter during the last vertical movement - Moved into its final position with an impact wrench-operated screw (the impact wrench not to be aligned in a vertical or horizontal position) - Alternatively, use of a worm gear to allow operation of the impact wrench in a horizontal position The pour spout section (horizontal movement) - Heater assembly picked up with a special attached crane tool to perform the horizontal positioning; dowel pins to provide accurate positioning OR - Heater assembly placed on a fixture (a

Table 2. Characteristics of Alternative Design Concepts (Cont)

		non-remotely replace able part attached to the pour spout section) using the melter cell crane or the canyon crane; vertical dowel pins to guide the heater assembly into its position on the fixture; impact wrench-operated fixture to horizontally move the assembly into its final position; horizontal dowel pins to provide accurate positioning
Alternative Design D (Figures 15a – 15c) • Two separate assemblies • U-shaped resistance elements arranged parallel to the riser and pour spout; the cold ends of the elements bent at 90°	• Four thermocouples (not separately replaceable) in the riser assembly • Two thermocouples (not separately replaceable) in the pour spout assembly	The riser hood assembly • Pre-positioned by combining vertical and horizontal movements using the Melter cell crane or the Canyon crane • Assembly lowered into its final position by a straight vertical movement • Dowel pins for accurate positioning The pour spout section (similar to alternate design C)
Alternative Design E (Figure 16) • Ceramic block heaters (high chromia-content) • Plate electrodes (Inconel 690) contacting two sides of the block • A secondary heater (U-shaped element) for the start-up • Developed by KfK² in Germany for melters in the PAMELA plant and other KfK facilities	• Secondary heater assemblies equipped with two or more thermocouples • One non-replaceable thermocouple in each electrode to control the ceramic heaters	• Ceramic blocks not replaceable (lifetime > 2 years) The pour spout section (similar to alternate design C) • Heater in the riser section must be inserted at an angle.

² Kernforschungszentrum Karlsruhe

Figure 12(a). Alternative A – Sectional View

Figure 12(b). Alternative A – Plan View

Figure 13(a). Alternative B – Sectional View

Figure 13(b). Alternative B – Plan View

Figure 14(a). Alternative C – Sectional View

Figure 14(b). Alternative C

Figure 15(a). Alternative D – Sectional View

Figure 15(b). Alternative D

Figure 15(c). Alternative D – Plan View

Figure 16. Alternative E - Sectional View

Table 3. Evaluation Criteria and Preselection of the Alternative Designs

Evaluation For Preselection of Alternatives						
Evaluation Criteria	Requirements/ Assumptions	Alternative "A"	Alternative "B"	Alternative "C"	Alternative "D"	Alternative "E" (Not Replaceable)
1. Temperature Distribution	1. Minimum glass temperature 1920°F	1. Meets criteria (uneven temp distribution in riser, even in pour spout)	1. Same as Alternative "A"	1. Meets criteria (even temp. distribution)	1. Meets criteria (even temp. distribution)	1. Meets criteria (even temp. distribution)
2. Heaters - Electrical Requirements - Replaceability - Life Span of Heating Elements - Mechanical Properties of Heating Elements	2. - Minimize no. of Connectors - Remotely replaceable - Assumed 12 months - No specific requirements	2. - Elect. Conn. + T.C. Conn. - Heaters + T.C. (Riser) Replaceable - 1-1/2 years - No sagging • Opr. temp.	2. - 3 Elect. + 2 T.C. Conn. - Same as A. Pour Spout + Riser section separately replaceable Same as A Same as A	2. - 2 Elect + 2 Instr. Conn. - Separate assy for Riser + Pour Spout T.C. replaceable heaters 1-1/2 years Same as A	2. - 2 Elect. + 2 Instr. Conn. - Same as C - 2 years - Support req'd to prevent sagging in Riser section (excessively brittle after heating)	2. - 2 Elect + 1 T.C. Conn. (hard wired to the frame) 1 Elect + 1 Instr. To startup heater - Startup heaters (only) replaceable - Over 3 years - Structurally strong
3. Thermocouples - Proper Location for Temp Control - Replaceability	3. - No specific requirement - Remotely replaceable	3. - Adequate for heating chamber control T.C. (Riser) replaceable T.C. (pour spout) not replaceable	3. - Same as A Same as A	3. - Same as A - T.C. replaceable w/heaters	3. - Same as A Same as C	3. - T.C. in each electrode - T.C. (electrode) not replaceable. T.C. (startup heater) replaceable
4. Mechanical Support for INCONEL 690 Riser (Trough)	4. Maintain position during transportation & operation	4. Good lateral support provided at the bottom of Riser and Pour Spout. Minimum lateral support at top of the Riser.	4. Same as A	4. Good support all along	4. Good support all along	4. Good support all along

Table 3. Evaluation Criteria and Preselection of the Alternative Designs (Cont.)

Evaluation For Preselection of Alternatives						
Evaluation Criteria	Requirements/ Assumptions	Alternative "A"	Alternative "B"	Alternative "C"	Alternative "D"	Alternative "E" (Not Replaceable)
5. Remote Handling - Tools - Complexity of Remote Handling	5. - Use available tools (canyon crane, impact wrench, MSM) if possible	5. - Replacement with available tools - Straight vertical lift of assembly	5. - Same as A - Straight vertical lift of assemblies	5. - May require add'l tools (e.g. KSNV) for replacement of Pour Spout heater assy, if MSM can't push - Compounding vert. + horiz. movements for Riser horiz. Installation for Pour Spout	5. - Same as C - Riser, same as A horizontal installation for Pour Spout	5. - Startup heater would require special guiding fixture - Startup heater requires installation at an angle with remoteable fixture
6. Impact on Other Components - Frame - Melter Cooling Water - Dome Heater Cover - Canister Positioning Arm - Pour Spout Bellows	6.	6. - Yes, (frame mod. req'd for vertical lift) - Yes, (relocate cooling water outlet nozzle on shell. Also modify cooling water path around riser at the shell/riser intersection. - Yes, major reroute of the C.W. piping to the dome heater covers - Remote elect./I&C jumpers cross crane access area for replacement or maintenance - No	6. - Mod. less than A (vertical lift smaller than A) - Same as A - Same as A - Same as A - No	6. - No - Mod. cooling water path around Riser • shell/Riser intersection - Minor rerouting - Same as A May have additional impact from Pour Spout heater assy - Yes - Riser installation assy blocks access to nuts on bellows assy	6. - No - Same as C mod. may not be required - Same as A - Same as C - No	6. - No - Yes, same as C - Minor rerouting Electrode terminals may interfere - Yes, electrode terminals limit access to Pour Spout Bellows pipe connectors

Table 3. Evaluation Criteria and Preselection of the Alternative Designs (Cont.)

Evaluation For Preselection of Alternatives						
Evaluation Criteria	Requirements/ Assumptions	Alternative "A"	Alternative "B"	Alternative "C"	Alternative "D"	Alternative "E" (Not Replaceable)
6. Impact on Other Components continued - Remote Connectors - CCTV Mounted on Melter Frame - Busbar for Electrodes (Rerouting)		- Yes, need 2 add'l on the wall - Yes mod. of camera support required - Yes, mod. of frame requires rerouting of busbar	- Yes, need 3 add'l on the wall - Yes, same as A - Same as A	- Yes, need 2 add'l on the wall - Yes, same as A - No	- Yes, need 2 add'l on the wall Yes, same as A - No	- Yes, need 3 add'l on the wall + 1 on the frame - Yes, same as A (minor mod. may be req'd) - No
7. Impact on Fabrication & Assembly	7.	7. Later	7. Later	7. Later	7. Later	7. Later
8. Reliability	8.	8. Potential for damage during installation	8. Same as A	8. Pour Spout heaters have potential for damage during installation	8. Heating elements are fragile, but better protected than A & B	8. No experience with geometry of cylindrical ceramic blocks
9. Maintainability	9. Components with life span shorter than melter must be remotely replaceable.	9. Complete heater assembly replaceable. Pour Spout T.C. not replaceable. Riser T.C. separately replaceable.	9. Same as with Riser & Pour Spout heaters separately replaceable	9. Riser & Pour Spout heaters separately replaceable. T.C. replaceable with heaters.	9 Same as C	9. Startup heater & T.C. replaceable. Ceramic block heaters not replaceable. T.C. electrodes not replaceable
10. Capital Cost	10. Later	10. Later	10. Later	10. Later	10. Later	10. Later
11. Additional Testing Required? - For Design - For Design Confirmation	11.	11. - Yes, design for compensation for thermal expansion of Riser/Pour Spout - Yes, the design needs to be tested for conformation (process and remote handling)	11. - Same as A - Same as A	11. - Same as A - Same as A	11. - Same as A - Same as A	11. - Same as A - Same as A

Table 4. Review Comments of the Alternative Designs

Alternative Design	Advantages	Disadvantages
A	• Easy vertical replacement of heater assembly and thermocouples	• Replacement of whole assembly for single element failure • Limited on amount of heater area available for power dissipation
B	• Flexibility to replace the riser and the pour spout heaters independently • Easy vertical replacement of heater assembly and thermocouples	• Limited on amount of heater area available for power dissipation
C	• Increased heating element area • Reduced watt loading • Even distribution of heat • Heaters connected in parallel (one element failure will not require full assembly replacement) • Flexibility to replace the riser and the pour spout heaters independently	• Complicated mounting and dismounting procedure for heater assemblies
D	• Possible advantage over A and B in heat distribution and watt loading	• Complicated mounting and dismounting procedure for heater assemblies • Concern elements may sag and fragility of MoSi₂
E	• Uniform heating • Low watt loading	• Complex (such as, primary and secondary heaters) yet demonstrated under remote conditions • Difficulty maintaining continuity (low contact resistance) between Inconel electrodes and ceramic blocks – could result in hot spots between the electrode and the blocks • Temperature limitations of Inconel (in case of hot spots) • High current requirement? • Blocks and electrodes not replaceable • Difficult replacement (angled) of start-up heater

4. Future Work and Recommendations

Based on a review of past design optimization activities and an assessment against more recent experience, the following recommendations were proposed by PNNL staff for future consideration:

1. **Install an access port above the pour spout:** This will aid inspection, repair, and replacement of pour spout inserts from the top. This option is expected to lead to better tool development and deployment (especially for replacing the tip). The main concern would be the vacuum sealing of this access port. However, proper design of the port to prevent in-leakage should be possible.
2. **Pour spout heater replacement:** Although the present heaters (Inconel 690) have surpassed their operating life projections they do have power and temperature limitations that do not allow operations approaching 1100°C. As a result, the glass viscosity in the pour spout is higher than would otherwise exist. This condition promotes wicking and dripping occurrences that hamper operation and pour spout plugging. Switching to a high temperature-heating element (ceramic or intermetallic) will provide more flexibility of operations. For example, the temperature could be increased to a higher value to avoid glass dripping. A replaceable ceramic assembly should be considered. The joint between the inconel spout component and ceramic section should be designed to minimize the mechanical and thermal stresses due to thermal expansion coefficient mismatch and the ceramic section can be replaced remotely. An appropriate level of thermal and mechanical stress modeling needs to be performed to support the design work.
3. **Pour tip materials:** There has been significant progress made in the area of hard materials development recently. A survey of the hard materials for application in the pour knife-edge and insert is proposed. A harder alternative material tip insert (for example carbides, composites, and even synthetic diamond) if available will reduce the erosive corrosion, extend the life of the tip, and reduce the frequency of replacement and down time. Any non-oxide component may need inert or reducing atmosphere or a protocol for handling the atmosphere to which the tip is exposed.
4. **Pour tip design:** The hydraulic behavior of the melt in the riser and pour spout area need to be evaluated to optimize the internal geometry and design of the riser/pour spout area. For example, a slope may be introduced that will change the dynamics of the melt flow to mitigate slug flow surges and flooding of the spout and to achieve a more repeatable flow stream. These designs may be analyzed using modeling and actual pour spout flow testing (similar to the work at the FIU). Alternate designs are expected to achieve steady flow.
5. **Robotic arms vs. crane:** Previous Hanford overflow redesign efforts were based on having to use an in-cell crane for all installation and maintenance activities. This necessitated the use of Hanford or Purex connectors. The availability of a robotic arm offers new prospects for design modifications. With robotic arms, the components and tools can be smaller and the overflow heater sections could be individually replaceable.
6. **Thermocouple:** Thermocouple replacement using the robotic arm should be considered as a means of eliminating thermocouple failures as a requirement for overflow section replacement or even melter replacement.

5. References

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TFA Technology Abstract – Annual Report on Clemson/INEEL Melter Work Status of Replacement Heater Modules for Pour Spout Heater (U) at:
<http://www.pnl.gov/tfa/back/abstracts/pourspoutheater.stm>

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APPENDIX A

4.70 ISOPARAMETRIC THERMAL SOLID

This element has a three-dimensional thermal conduction capability. The element has eight nodal points with a single degree of freedom, temperature, at each node. The element is applicable to a three-dimensional, steady-state or transient, Thermal (KAN=-1) analysis. The element also can compensate for mass transport heat flow from a constant velocity field. If the model containing the conducting solid element is also to be analyzed structurally, the element should be replaced by an equivalent structural element (such as STIF45), see Section 2.21, Thermal-Stress Procedure. A similar thermal element, with mid-edge node capability, is described in Section 4.90 (STIF90).

An option exists that allows the element to model nonlinear steady-state fluid flow through a porous medium. With this option, the thermal parameters are interpreted as analogous fluid flow parameters. For example, the temperature degree of freedom becomes equivalent to a pressure degree of freedom.

4.70.1 Input Data

The geometry, nodal point locations, face numbers, loading, and the coordinate systems for the element are shown in Figure 4.70.1. The element is defined by eight nodal points and the orthotropic material properties. Orthotropic material directions correspond to the element coordinate directions. The element coordinate system orientation is as described in Section 4.0.12. The specific heat and density may be assigned any value for steady-state solutions. Properties not input default as described in Section 4.0.2. An average internal heat generation rate may be applied to the element. All of the element surfaces have convection capability and are numbered as shown in Figure 4.70.1.

The nonlinear porous flow option is selected with KEYOPT(7)=1. The permeabilities are defined in the global X, Y, and Z directions. Section 4.70.3 lists the analogous variables used with this option. If KEYOPT(7)=1, temperature boundary conditions input with the NT command are interpreted as pressure boundary conditions, and heat flow boundary conditions input with the HFLOW command are interpreted as mass flow rate (mass/time). A summary of the thermal solid element parameters is given in Table 4.70.1. A general description of element input is given in Section 4.0.2.

4.70.2 Output Data

a) Printout - The solution printout associated with the thermal solid element is in two forms: 1) the node temperatures are included in the overall nodal temperature solution printout, and 2) the element printout is as shown in Table 4.70.2. Heat flowing out of the element is considered to be positive. The element output directions are parallel to the element coordinate system. The heat flow rate at the nodes can be printed with the KRF command. If KEYOPT(7)=1, the standard thermal output should be interpreted as the analogous fluid flow output. A general description of element printout is given in Section 4.0.3.

b) Post Data - The post data associated with the element is shown below. The data are written on File12 if requested, as described in Section 4.0.4.

1 TGSUM	11 TAVG(1)	69 TOTAL VELOCITY
2 TFSUM	12 TBULK(1)	70-72 VELOCITY(X,Y,Z)
3 VOL	13 HT RATE(1)	73-75 TG(X,Y,Z)
4 FACE NO.	14-63 4-13 @ (2-6)	76-78 TF(X,Y,Z)
5 AREA(1)	64 TOTAL PR GRAD	3-----
6-9 FACE NODES(1)	65-67 PRESS GRAD(X,Y,Z)	
10 HFILM(1)	68 MASS FLUX	

Items 5 through 13 for each face are zero unless convection is present. Items 64 through 72 are zero unless KEYOPT(7) = 1.

4.70.3 Theory

The temperature distribution for this element is obtained from the numerical solution of the following equation:

$$\rho C_p \left(\frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + v_z \frac{\partial T}{\partial z} \right) = \frac{\partial}{\partial x} \left(k_{xx} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_{yy} \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_{zz} \frac{\partial T}{\partial z} \right) + \ddot{q}$$

where: ρ = density (Weight (or Mass)/Volume)

C_p = specific heat (Heat/Weight (or Mass)*Degree)

k = thermal conductivity (Heat/Length*Time*Degree)

$\ddot{q}$ = internal heat generation rate (Heat/Volume*Time)

v = velocity for the mass transport option (KEYOPT(8)>0 only)

The temperature functions used for the element are trilinear as described in Section 2.70 of the ANSYS Theoretical Manual (Ref. 5). A 2x2x2 lattice of integration points is used for the numerical (Gaussian) integration procedure.

For the nonlinear porous flow option (KEYOPT(7)), the pressure distribution is obtained by the above equation (where T is interpreted as pressure and k_{xx} , k_{yy} , and k_{zz} are interpreted as the coefficients of permeability) with C_p and $\ddot{q}$ defined to be zero. The coefficients of permeability are internally calculated for each direction as

$$k = \frac{K\rho}{\mu + K\rho V^\alpha}$$

where

K = absolute permeability of the medium (length²) - input as property KXX, KYY, or KZZ corresponding to the desired direction.

ρ = mass density of the fluid (mass/volume) - input as property DENS

μ = viscosity of the fluid (force*time/length²) - input as property VISC

β = visco-inertial parameter of the fluid (1/length) – input as property C

V = total (vector magnitude) fluid velocity (length/time) – internally calculated

α = exponent on velocity – input as property MU

Note that since properties may be temperature dependent, the above input terms may be analogously interpreted as being pressure dependent.

4.70.4 Assumptions and Restrictions

The element must not have a zero volume. This occurs most frequently when the element is not numbered properly. Elements may be numbered either as shown in Figure 4.70.1 or may have the planes IJKL and MNOP interchanged. A prism or tetrahedron shaped element may be formed by defining duplicate node numbers as described in Section 4.0.9.

The specific heat is evaluated at each integration point to allow for abrupt changes (such as for melting) within a coarse grid. If the thermal element is to be replaced by a STIF45 structural element with surface stresses requested, the thermal element should be oriented such that Face 2 and/or Face 4 is a free surface.

A free surface of the element (i.e., not adjacent to another element and not subjected to a boundary constraint) is assumed to be adiabatic. Thermal transients having a fine integration time step and a severe thermal gradient at the surface will also require a fine mesh at the surface, see Section 2.21. With the mass transport option, temperatures should be specified along the entire inlet boundary to assure a stable solution.

Figure 4.70.1 3-D Isoparametric Thermal-Electric Solid

TABLE 4.70.1

3-D ISOPAR. THERMAL SOLID

ELEMENT NAME	STIF70
NO. OF NODES	8 I, J, K, L, M, N, O, P
DEGREES OF FREEDOM	1 TEMP
REAL CONSTANTS	3 VX, VY, VZ IF KEYOPT(8)>0
MATERIAL PROPERTIES	5 KXX, KYY, KZZ, DENS, C, 7 VISC, MU (USED ONLY IF KEYOPT(7)=1)
CONVECTION FACES	6 IJKL, IJNM, JKON, KLPO, LIMP, MNOP
HEAT GENERATION RATES	1 AVERAGE
SPECIAL FEATURES	UNSYMMETRIC MATRICES (IF KEYOPT(8)>0)
KEYOPT(2)	0 - EVALUATE FILM COEFFICIENT (IF ANY) AT AVERAGE FILM TEMPERATURE, $(TS + TB)/2$ 1 - EVALUATE AT ELEMENT SURFACE TEMPERATURE, TS 2 - EVALUATE AT FLUID BULK TEMPERATURE, TB 3 - EVALUATE AT DIFFERENTIAL TEMPERATURE TS-TB
KEYOPT(4)	USED ONLY WITH KEYOPT(8)>0 0 - VX, VY AND VZ ARE IN THE ELEMENT COORDINATE SYSTEM 2 - VX, VY AND VZ ARE BASED ON SIDE I-J (VX ALONG TO THE ELEMENT I-J SIDE, VY IN IJK PLANE, VZ NORMAL TO VX AND VY)
KEYOPT(7)	0 - STANDARD HEAT TRANSFER ELEMENT 1 - NONLINEAR STEADY-STATE FLUID FLOW ANALOGY ELEMENT (TEMP. DEG. OF FREEDOM INTERPRETED AS PRESSURE)
KEYOPT(8)	0 - NO MASS TRANSPORT EFFECTS 1 - MASS TRANSPORT WITH VX, VY, VZ

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TABLE 4.70.2

3-D ISOPAR. THERMAL SOLID
ELEMENT PRINTOUT EXPLANATIONS

LABEL	NUMBER OF CONSTANTS	EXPLANATION
LINE 1		
EL	1	ELEMENT NUMBER
NODES	8	NODES - I,J,K,L,M,N,O,P
MAT	1	MATERIAL NUMBER
VOL	1	VOLUME
LINE 2		
TG(X,Y,Z,SUM)	4	THERMAL GRADIENT COMPONENTS AND VECTOR SUM AT CENTROID
TF(X,Y,Z,SUM)	4	THERMAL FLUX (HEAT FLOW RATE/CROSS-SECTIONAL AREA) COMPONENTS AND VECTOR SUM AT CENTROID
LINE 3 (PRINTED ONLY IF CONVECTION)		
FACE	1	CONVECTION FACE NUMBER
NODES	4	NODES ON THIS FACE
AREA	1	CONVECTION FACE AREA
HF	1	FILM COEFFICIENT
TAVG,TBULK	2	AVERAGE FACE TEMP, FLUID BULK TEMP.
HEAT RATE	1	HEAT FLOW RATE ACROSS FACE
LINES 4-8 (SAME AS ABOVE FOR OTHER CONVECTION FACES, IF DEFINED)		
LINE 2 (ALT.) (PRINTED ONLY IF KEYOPT(7) = 1)		
PRESSURE GRAD	4	TOTAL PRESSURE GRADIENT AND ITS X, Y, AND Z COMPONENTS
LINE 3 (ALT.) (PRINTED ONLY IF KEYOPT(7) = 1)		
MASS FLUX	1	MASS FLOW RATE PER UNIT CROSS-SECTIONAL AREA
FLUID VELOCITY	4	TOTAL FLUID VELOCITY AND ITS X, Y, AND Z COMPONENTS

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APPENDIX B

D.12 SUBSTRUCTURE RADIATION MATRIX GENERATION (File8) UTILITY

This utility constructs a substructure radiation matrix from user inputs of emissivity (ϵ) and geometry. The emissivity may be a function of material. The geometry may be any plane 2-D or 3-D model prepared in PREP7 and written to node and element files with the NWRITE and EWRITE commands of the GWRITE module. Only nodes and elements on the radiating edge of a 2-D model or face of a 3-D model are used by AUX12. A 2-D solid model of STIF55 elements, for example, would require line elements (such as STIF32) to be overlayed along the edge nodes. Similarly, shell elements (such as STIF57) could be overlayed along the radiating faces of a 3-D STIF70 model. Only the edge nodes and the "lining" elements should be written to the files since AUX12 uses only 2-noded line elements for 2-D models and 4-noded area elements for 3-D models.

The orientation of the element is based on its normal from face 1. For this utility, face 1 of area elements is on the element +z side, and for line elements, on the +y side (x from Node I to J). The PREP7 model should be verified with the /NORMAL command before files are written for AUX12. The element view is a unit hemisphere from the face 1 normal on a 3-D solid element, and a unit semicircle from a 2-D element face normal. The other elements are projected onto the unit surface of the first element and a user-defined number of equal energy rays are distributed over the element's viewing sphere. The number of rays incident on each element is calculated and the ratio of the incident rays, divided by the total rays for each element is the element-to-element view factor. Element view factors are distributed to the nodes and summed at nodes common to adjacent elements. The nodal view factor is combined with the emissivity and the area, and the result written as a radiation matrix.

The view factor calculations are based on gray body diffuse radiation by either of two procedures. The first is the "hidden" procedure which uses a hidden-line algorithm to determine which elements are visible to every other element. This procedure is recommended when the geometry has portions possibly not visible to other portions. The hidden procedure can also generate an unsymmetric matrix but the degree of unsymmetry is directly related to the mesh density and the results should be carefully interpreted. The other method is the "non-hidden" procedure which calculates the view factor from every element to every other element in its viewing hemisphere, regardless of any blocking elements. The non-hidden procedure is faster than the hidden procedure since it doesn't use the hidden-line algorithm.

The calculated matrix is used as a substructure in the Thermal (KAN=-1) analysis with KEYOPT(1)=1 for the STIF50 element type. A brief description of the calculation procedure is as follows: The terms in the matrix are of the form $A\epsilon F\sigma$ for the expression

$$\{Q\} = A\epsilon F\sigma (T_i^4 - T_j^4).$$

In matrix form, these equations are:

$$[C]\{Q\} = [D]\{T^4\} \quad \text{or} \quad \{Q\} = [K]\{T^4\}$$

where: $[K] = [C^{-1}][D]$ is the "conductivity" matrix for the radiation model, and is written as a substructure on FILE8 (default). See the ANSYS Theoretical Manual for details.

Substructure Radiation Matrix Generation Example

The following example shows the generation of a substructure matrix representing the radiation between two gray body parallel plates. The plates are represented by a unit area each. The Thermal analysis uses this substructure to find the temperature of one plate subjected to a specified heat flow and radiation from the other plate.

/PREP7	*	BEGIN PREP7 PREPROCESSING (AT ANSYS ROUTINE BEGIN LEVEL)
KAN,-1	*	THERMAL ANALYSIS
ET,1,57	*	ELEMENT TYPE 1 IS A THERMAL SHELL (STIF57)
N,1 \$N,2,...,1	*	DEFINE NODES
N,3,,1,1		
N,4,,1		
NGEN,2,4,1,4,1,1		
E,1,4,3,2	*	DEFINE ELEMENTS (NOTE ELEMENT ORIENTATION HAS
E,5,6,7,8	*	ELEMENTS FACING EACH OTHER)
NWRITE	*	WRITE NODES TO FILE15
EWRITE	*	WRITE ELEMENTS TO FILE14
FINISH	*	TERMINATE PREP7 ROUTINE
/AUX12	*	REQUEST RADIATION UTILITY (AT ANSYS ROUTINE BEGIN LEVEL)
WRITE	*	WRITE RADIATION SUBSTRUCTURE MATRIX TO FILE8
FINISH	*	TERMINATE UTILITY ROUTINE
/PREP7	*	BEGIN PREP7 PREPROCESSING PHASE FOR ANALYSIS DATA
/TITLE, THERMAL ANALYSIS BETWEEN TWO RADIATING BODIES (USING SUBSTRUCTURES)		
KAN,-1	*	THERMAL ANALYSIS
ET,1,50,1	*	ELEMENT TYPE 1 IS A RADIATION SUBSTRUCTURE
DOF,TEMP	*	TEMP IS THE DEGREE OF FREEDOM
TOFFSET,460	*	ABSOLUTE TEMPERATURES
E,1,8	*	ELEMENT 1 IS MATRIX 1 FROM FILE8
ITER,-10,1,1	*	UP TO 10 ITERATIONS
TUNIF,500	*	SPECIFY APPROXIMATE STARTING TEMPERATURE
KRF,1	*	PRINT NODAL HEAT FLOWS
KBC,1	*	HOLD LOADS CONSTANT
NT,1,TEMP,1000,,4,1	*	SPECIFY TEMPERATURE AT NODES 1 THRU 4
HFLOW,2,HEAT,5,,8,1	*	SPECIFY HEAT FLOW AT NODES 2 THRU 8
AFWRITE	*	WRITE ANALYSIS FILE27
FINISH	*	TERMINATE PREP7 ROUTINE
/INPUT,27	*	BEGIN SOLUTION PHASE
FINISH	*	TERMINATE SOLUTION PHASE

TABLE D.12

SUBSTRUCTURE RADIATION MATRIX GENERATION UTILITY (AUX12) COMMAND SUMMARY

NFILE Defines the ANSYS data file where the node data are to be found.
 EFILE Defines the ANSYS data file where the element data are to be found.
 MFILE Defines the ANSYS data file where the calculated matrix is to be written.
 EMIS Specifies the emissivity associated with a material number.
 STEF Specifies Stefan-Boltzmann radiation constant.
 VTYPE Specifies the type of viewing procedure used to determine the view factors.
 GEOM Defines the geometry specifications.
 SPACE Defines space node.
 MPRINT Prints the element and node matrices when the WRITE command is issued.
 WRITE Writes matrix file (File8) for input to the substructure Thermal "use" pass.

*****

AUX12 DATA INPUT EXPLANATIONS

NFILE,Fname,Ext - Defines the ANSYS data file where the node data are to be found. If a name is used, assign named file to unit 15. If a number N is used, use whatever file is currently assigned to unit N. Command default - File15.

Fname - File name (8 char. max) assigned to unit 15. If N, use file unit N.
 Ext - File name extension (optional) (8 char. max.). See also Section 2.33.

EFILE,Fname,Ext - Defines the ANSYS data file where the element data are to be found. Similar to NFILE described above except uses unit 14 and defaults to File14.

MFILE,Fname,Ext - Defines the ANSYS data file where the calculated matrix is to be written. Similar to NFILE described above except uses unit 8 and defaults to File8. All matrices must be written to the same file.

EMIS,MAT,EVALU- Specifies the emissivity associated with a material number. A material number is also associated with each element read from the element file. Command default - Emissivity value of 1.0 associated with all materials.

MAT - Material number associated with this emissivity (100 max.).
 EVALU - Emissivity for this material ($0.0 < EVALU \leq 1.0$).

STEF,VALUE - Specifies Stefan-Boltzmann radiation constant. Command default - $0.119E-10 \text{ Btu/hr/in}^2/\text{°R}^4$

VALUE - Stefan-Boltzmann constant (defaults to above value).

6.13 SUBSTRUCTURE RADIATION MATRIX GENERATION

Overview

According to the Stefan-Boltzman Law, also used in Section 2.31, the heat transfer rate, Q , between two surfaces i and j due to radiation is:

$$Q_i = \sigma \epsilon_i F_{ij} A_i (T_i^4 - T_j^4) \quad (6.13.1)$$

where: Q_i = heat transfer rate from surface i

σ = Stefan-Boltzman constant

ϵ_i = effective emissivity

F_{ij} = view factor from surface i to surface j

A_i = area of surface i

T_i, T_j = absolute temperature at surface i and surface j , respectively

or

$$Q_i = K (T_i^4 - T_j^4) \quad (6.13.2)$$

where: K = effective conductivity due to radiation = $\sigma \epsilon_i F_{ij} A_i$

Equation (6.13.2) is not linear and cannot be solved using the linear equation solver.

Therefore, equation (6.13.1) is expanded as:

$$Q_i = \sigma \epsilon_i F_{ij} A_i (T_i^2 + T_j^2) (T_i + T_j) (T_i - T_j) \quad (6.13.3)$$

or

$$Q_i = K' (T_i - T_j) \quad (6.13.4)$$

where: $K' = \sigma \epsilon_i F_{ij} A_i (T_i^2 + T_j^2) (T_i + T_j)$

K' cannot be calculated directly since it is a function of the unknowns T_i and T_j .

The temperatures from previous iterations are used to iteratively calculate K' .

The above procedure is not appropriate for complex models where it is impractical to input the view factors or where the view factors may not be available. A more general expression of radiation heat transfer using gray body diffuse radiation theory (equation (8-19), Siegal(88)) for an enclosed system of N radiating surfaces is:

$$\sum_{i=1}^N \left(\frac{\delta_{ji}}{\epsilon_i} - F_{ji} \frac{1-\epsilon_i}{\epsilon_i} \right) \frac{1}{A_i} Q_i = \sum_{i=1}^N (\delta_{ji} - F_{ji}) \sigma T_i^4 \quad (6.13.5)$$

where:

$$\delta_{ji} = \text{Kronecker delta} = \begin{cases} 1, & \text{when } j = i \\ 0, & \text{when } j \neq i \end{cases}$$

This equation can be used to construct a single row in the following matrix equation:

$$[C]\{Q\} = [D]\{T^4\} \quad (6.13.6)$$

such that:

$$\text{each row } j \text{ in } [C] = \sum_{i=1}^N \left(\frac{\delta_{ji}}{\epsilon_i} - F_{ji} \frac{1-\epsilon_i}{\epsilon_i} \right) \frac{1}{A_i} \quad (6.13.7)$$

$$\text{each row } j \text{ in } [D] = \sum_{i=1}^N (\delta_{ji} - F_{ji}) \sigma \quad (6.13.8)$$

Solving for $\{Q\}$:

$$\{Q\} = [K^{ts}]\{T^4\} \quad (6.13.9)$$

and therefore:

$$[K^{ts}] = [C]^{-1}[D] \quad (6.13.10)$$

Equation (6.13.6) is analogous to equation (6.13.2) and can be linearized in a similar manner, such that:

$$\{Q\} = [K']\{T\} \quad (6.13.11)$$

$[K']$ now includes T^3 terms and is calculated in the same manner as in equation (6.13.4).

To be able to include radiation effects in elements other than STIF31, ANSYS uses STIF50 (the substructure element) to bring in the radiation matrix. STIF50 has an option that instructs the solution phase to calculate $[K']$. The AUX12 utility is used to create the substructure radiation matrix. AUX12 calculates the effective conductivity matrix, $[K^{ts}]$, in equation (6.13.9), as well as the view factors required for finding $[K^{ts}]$. The user defines flat surfaces to be used in AUX12 by overlaying nodes and elements on the radiating edge of a two-dimensional model or the radiating face of a three-dimensional model.

SUBSTRUCTURE RADIATION MATRIX GENERATION

View Factors

The view factor, F_{ij} , is defined as the fraction of total radiant energy that leaves surface i which arrives directly on surface j , as shown in Figure 6.13.1. It can be expressed by the following equation:

Figure 6.13.1 View Factor Calculation Terms

$$F_{ij} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{\cos \theta_i \cos \theta_j}{\pi r^2} d(A_j) d(A_i) \quad (6.13.12)$$

where: A_i, A_j = area of surface i and surface j
 r = distance between differential surfaces i and j
 θ_i = angle between N_i and the radius line to surface $d(A_j)$
 θ_j = angle between N_j and the radius line to surface $d(A_i)$
 N_i, N_j = surface normal of $d(A_i)$ and $d(A_j)$

The view factor, therefore, has these characteristics:

1. It is inversely proportional to the square of the distance between surfaces ($1/r^2$). The further surface j is away from surface i , the less radiation it receives from surface i .
2. It is proportional to $\cos \theta_i$. Surface i radiates the greatest amount of energy normal to surface j . Parallel to surface j the radiation is zero.
3. It is proportional to $\cos \theta_j$. Surface j absorbs the greatest amount of radiation normal to surface i . For radiation parallel to surface i , the absorption is zero.

Two methods are available to calculate the view factors (input quantity NOHID on the VTYPE command). The first method is called the non-hidden procedure. This method calculates a view factor for every surface to every other surface whether the view is blocked by an element or not. This simplified method uses equation (6.13.12) and assumes that all the variables are constant, so that the equation becomes:

$$F_{ij} = \frac{A_j}{\pi r^2} \cos \theta_i \cos \theta_j \quad (6.13.13)$$

The second method, called the hidden procedure, numerically calculates the view factor in the following conceptual manner. The hidden-line algorithm is first used to determine which surfaces are visible to every other surface. Then, each radiating, or "viewing," surface (i) is enclosed with a hemisphere of unit radius. This hemisphere is oriented in a local coordinate system (x'y'z'), whose center is at the centroid of the surface with the z-axis normal to the surface, the x-axis is from node I to node J, and the y-axis orthogonal to the other axes. The receiving, or "viewed," surface (j) is projected onto the hemisphere exactly as it would appear to an observer on surface i.

Figure 6.13.2 Receiving Surface Projection

As shown in Figure 6.13.2, the projected area is defined by first extending a line from the center of the hemisphere to each node defining the surface or element. That node is then projected to the point where the line intersects the hemisphere and transformed into the local system $x'y'z'$, as described in Section 5.17 of Kreyszig(23). This projected area accounts for both the distance effect (characteristic 1) and the θ_j effect (characteristic 3).

The effect of θ_i (characteristic 2) is accounted for by projecting a user-defined number of discrete rays from the center of the hemisphere to the hemisphere surface. The number of rays is defined as follows:

$$N_r = \begin{cases} 2(N_z), & \text{if two-dimensional} \\ 2(N_z)(N_z+1), & \text{if three-dimensional} \end{cases} \quad (6.13.14)$$

where: N_r = number of rays

N_z = number of radial zones (input quantity NZONE, VTYPE command)

The rays are distributed on the hemisphere using the equation of a sphere:

$$x'^2 + y'^2 + z'^2 = 1 \quad (6.13.15)$$

such that:

$$x' = \begin{cases} \frac{2n-N_r-1}{N_r}, & \text{if two-dimensional } (n = 1 \text{ to } N_r) \\ R_n \cos \phi_{nm}, & \text{if three-dimensional} \end{cases} \quad (6.13.16)$$

$$y' = \begin{cases} 0, & \text{if two-dimensional} \\ R_n \sin \phi_{nm}, & \text{if three-dimensional} \end{cases} \quad (6.13.17)$$

$$z' = \begin{cases} \sqrt{1 - x'^2}, & \text{if two-dimensional} \\ \sqrt{1 - R_n^2}, & \text{if three-dimensional} \end{cases} \quad (6.13.18)$$

where:

$$R_n = \frac{2n-1}{2N_z} \quad (n = 1 \text{ to } N_z)$$

$$\phi_{nm} = \frac{\pi(2m-1)}{4n} \quad (m = 1 \text{ to } 4n \text{ for each } n = 1 \text{ to } N_z)$$

The view factor, F_{ij} , is determined by counting the number of rays striking the projected surface j and dividing by the total number of rays (N_r) emitted by surface i . This method may violate the radiation reciprocity rule, that is, $A_i F_{i-j} \neq A_j F_{j-i}$.

Space Node

A space node may be defined (SPACE command) to absorb all energy not radiated to other elements. Any radiant energy not incident on any other part of the model will be directed to the space node. If the model is not a closed system, then the user must define a space node with its appropriate boundary conditions.

Calculation of [K]

Equation (6.13.10) gives the equation of $[K^{ts}]$ based on the surfaces. The substructure radiation matrix requires a nodal matrix; therefore, the surface-to-surface $[K^{ts}]$ matrix as calculated by equation (6.13.10) must be converted to a node-to-node $[K^{tn}]$ matrix. Each term of the surface matrix corresponds to a n by n submatrix in the nodal matrix, where n is the number of nodes per surface. Therefore, $[K^{tn}]$ is a N by N matrix, where N is the total number of nodes in the model. If a space node is specified, then it is assigned the nodal location $(N+1)$ and $[K^{tn}]$ is now a $(N+1)$ by $(N+1)$ matrix. The transformation used in AUX12 to find each nodal row in the matrix $(K_{i,j}^{tn})$ is developed in the following steps:

1. The off-diagonal term representing the energy leaving node i and going to the space node $(N+1)$:

$$K_{i,N+1}^{tn} = \sum \frac{\Psi_i}{n} \quad (6.13.19)$$

where: N = total number of nodes in model

n = number of nodes per element

Ψ = any $[K^{ts}]$ term whose surface contains either node i or j

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2. The off-diagonal terms for node i are:

$$K_{i,j}^{tn} = \begin{cases} 0, & \text{if nodes } i \text{ and } j \text{ share the same element} \\ \sum \frac{\Psi_j}{n \times n}, & \text{if nodes } i \text{ and } j \text{ do not share the same element} \end{cases} \quad (6.13.20)$$

3. The on-diagonal term for node i is:

$$K_{i,i}^{tn} = \sum \text{of the off-diagonal terms in row } i \text{ calculated in steps 1 and 2} \quad (6.13.21)$$

4. Terms of the $(N+1)$ space node row:

$$K_{N+1,j}^{tn} = K_{j,N+1}^{tn} \quad (6.13.22)$$

and

$$K_{N+1,N+1}^{tn} = - \sum_{k=1}^N K_{N+1,k}^{tn}$$

If a space node is specified, the terms calculated in steps 1 and 4 are assigned to the space node $(N+1)$. In the radiation substructure use-pass the radiation matrix file formed by AUX12 will be modified by forcing the diagonal term to be equal and opposite to the sum of the off-diagonal terms. Based on the theory of a closed radiating system, this operation is valid, since it maintains energy balance. The diagonal term computed in AUX12 will be equal and opposite to the sum of the off-diagonal terms only if the model is a closed system. The open system will maintain a heat balance only if a space node is defined.

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