THERMAL ANALYSIS FOR THE CRYOGENIC FLUID

MANAGEMENT FLIGHT EXPERIMENT (CFMFE)

BY

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THERMAL ANALYSIS FOR THE CRYOGENIC FLUID MANAGEMENT

FLIGHT EXPERIMENT (CFMFE)

o   CRYOGENIC FLUID THERMAL ANALYSES FOR SPACE WERE INITIATED IN THE LATE FIFTIES

o   TODAY, CRYOGENIC FLUIDS ARE ROUTINELY USED (OR CONSIDERED FOR USE) IN MANY SPACE
    APPLICATIONS

    o   LAUNCH VEHICLES

    o   LONG TERM STORAGE FOR PROPULSION OR LIFE SUPPORT

    o   SENSOR COOLING

    o   REFRIGERATION

    o   SUPPLY OR RESUPPLY OF PROPULSION STAGES, SATELLITES AND SPACE STATIONS

o   CFMFE OBJECTIVE - PROVIDE DATA FOR THE DESIGN OF EFFICIENT, CRYOGENIC FLUID MANAGEMENT
    SYSTEMS IN A SPACE ENVIRONMENT

o   PURPOSES OF THIS PAPER

    o   IDENTIFY RECENT CFMFE THERMAL ANALYSIS EFFORTS

    o   REVIEW A SMALL PART OF THIS ANALYSIS WORK - THE PREDICTION OF FLUID AND CONTAINER
        TEMPERATURE GRADIENTS DURING LOW GRAVITY STORAGE IN SPACE

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CFMFE THERMAL ANALYSES

o   EARLY REPORTS

     o   MARTIN MARIETTA
     o   GENERAL DYNAMICS
     o   BEECH

o   RECENT REPORTS

     o   MARTIN MARIETTA
          CFMF FLUID AND THERMAL ANALYSIS REPORT
          CRYOGENIC SYSTEMS ANALYSIS MODEL (CSAM) USER'S MANUAL

     o   NASA-LERC
          THERMODYNAMIC MODELING OF RECEIVER TANK FILLING - AYDELOTT, CHATO AND DEFELICE
          DUMPING OF TANKS ON ORBIT - CHATO
          SUPPLY TANK VENT CALCULATIONS - LACOVIC

     o   ANALEX CORPORATION
          CSAM - NAKANISHI
          PRESSURE VESSEL THERMAL DESIGN - NAKANISHI
          MULTILAYER INSULATION - NAKANISHI
          FLUID AND THERMAL ANALYSIS - NAKANISHI
          TWO DIMENSIONAL FINITE ELEMENT ANALYSIS METHOD FOR
               THERMAL CONDUCTION PROBLEMS - NAKANISHI
          PRESSURE VESSEL AND FLUID TEMPERATURE PREDICTIONS
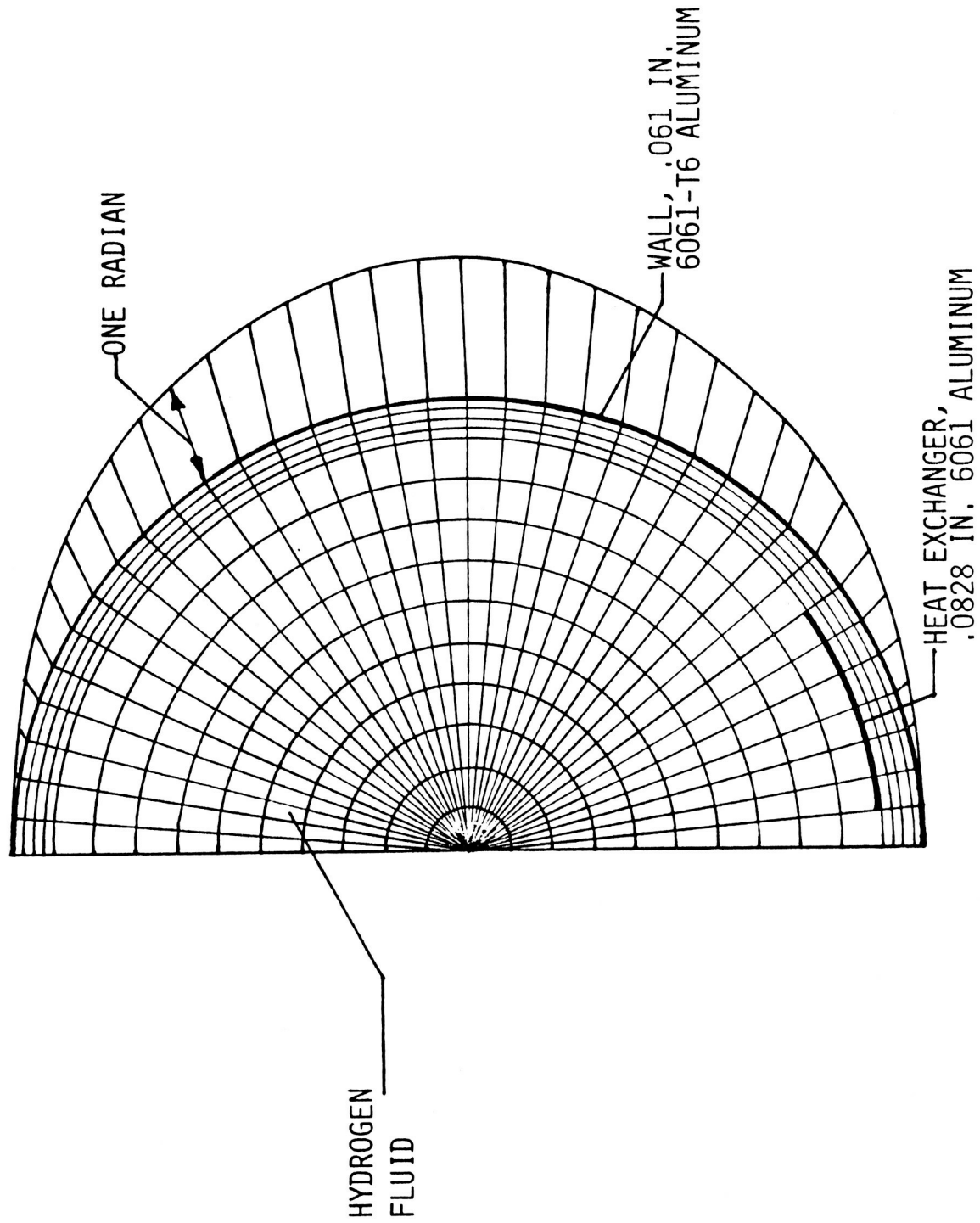   USING SINDA THERMAL MODELS - SMOLAK

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PRESSURE VESSEL AND FLUID TEMPERATURE PREDICTIONS USING

SINDA THERMAL MODELS

o   MODEL GEOMETRY - THREE DIMENSIONAL WEDGE

     SMALL SPHERE - 22 CUBIC FEET VOLUME
     LARGE SPHERE - 200 CUBIC FEET VOLUME

o   MODES OF HEAT TRANSFER

     CONDUCTION
     CONVECTION

o   ULLAGE SURFACE SHAPES

     SPHERICAL
     FLAT

o   HEATING/COOLING

     WALL HEATING - UNIFORM DISTRIBUTION
     COOLING WITH HEAT EXCHANGERS
          INTERNAL
          EXTERNAL

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NODE LAYOUT FOR SINDA SPHERICAL

WEDGE MODEL OF CFMFE 22 CUBIC FOOT TANK

ONE RADIAN

WALL, .061 IN.
6061-T6 ALUMINUM

HEAT EXCHANGER,
.0828 IN. 6061 ALUMINUM

HYDROGEN
FLUID

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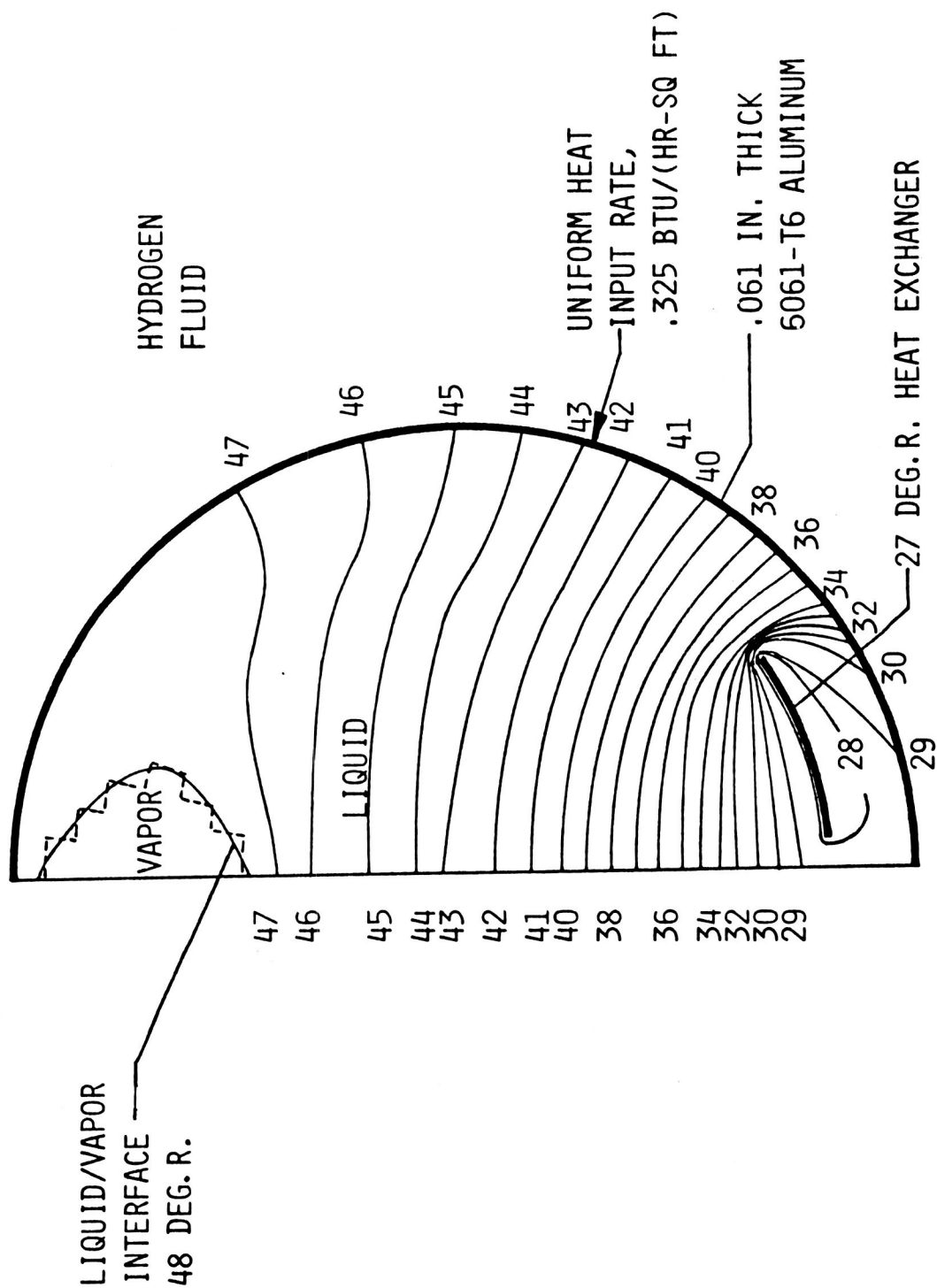SIMPLIFYING ASSUMPTIONS FOR SINDA WEDGE MODELS

o NO TEMPERATURE GRADIENTS NORMAL TO HEMISPHERICAL PLANE OF WEDGE

o CONDUCTION IN LIQUID, VAPOR AND WALL

o NO CONVECTION (EXCEPT AS NOTED LATER)

o NO RADIATION

o UNIFORM TEMPERATURE AT LIQUID/VAPOR INTERFACE

o THERMOPHYSICAL PROPERTIES OF FLUID AND SOLIDS TEMPERATURE DEPENDENT

o WEDGE THICKNESS - 1 RADIAN

o RADIAL HEIGHT OF NODES - 2 INCHES (EXCEPT 0.25 INCHES FOR NODES HAVING RADIUS
   EXCEEDING HEAT EXCHANGER RADIUS)

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STEADY STATE TEMPERATURE CONTOURS FOR A 22 CUBIC FOOT TANK

o   A SPHERICAL VAPOR BUBBLE WAS ASSUMED FOR ZERO GRAVITY

o   INTERNAL HEAT EXCHANGER (HEAT SINK) IS DOWNSTREAM OF LIQUID VENTED THROUGH AN
     EXPANSION VALVE

o   UNIFORM HEATING OF WALL (0.325 BTU/HR-SQ FT)

o   TEMPERATURE GRADIENT AROUND HEAT EXCHANGER IS STEEP

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STEADY STATE TEMPERATURE
CONTOURS FOR 22 CUBIC FOOT TANK

HYDROGEN FLUID

UNIFORM HEAT INPUT RATE, .325 BTU/(HR-SQ FT)

.061 IN. THICK 6061-T6 ALUMINUM

27 DEG. R. HEAT EXCHANGER

LIQUID/VAPOR INTERFACE 48 DEG. R.

VAPOR

LIQUID
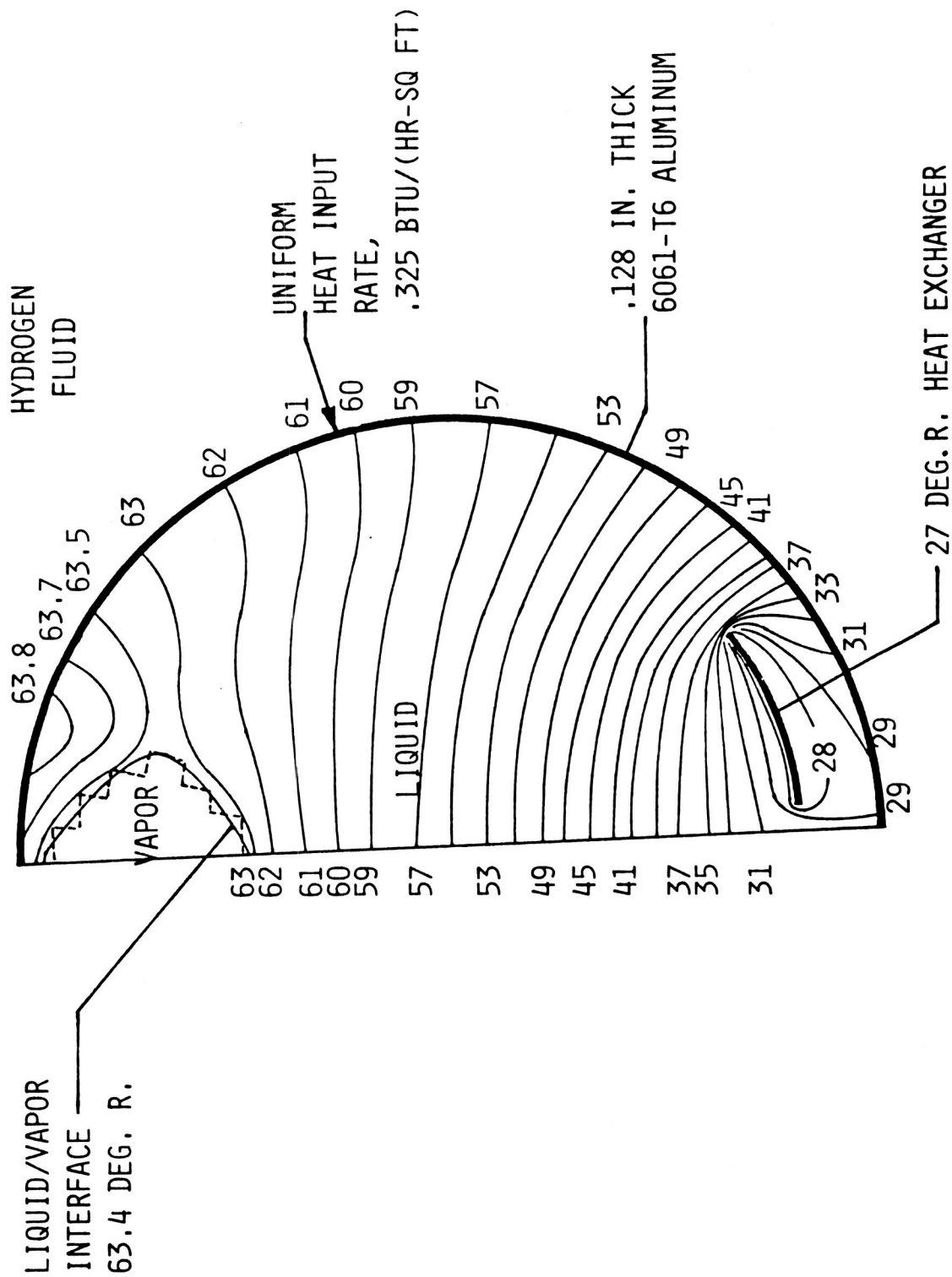
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STEADY STATE TEMPERATURE CONTOURS FOR A 200 CUBIC FOOT TANK

o   THESE ARE STEADY STATE, ZERO GRAVITY TEMPERATURE GRADIENTS FOR HYDROGEN IN A
    200 CUBIC FOOT TANK WITH A WALL THICKNESS OF 0.128 INCHES

o   IT APPEARS THAT IN THIS LARGER TANK CONDUCTION IS INADEQUATE RESULTING IN A
    LARGE TEMPERATURE RISE BETWEEN THE INTERNAL, COLD HEAT EXCHANGER AND
    THE LIQUID/VAPOR INTERFACE

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STEADY STATE TEMPERATURE
CONTOURS FOR 200 CUBIC FOOT TANK

HYDROGEN
FLUID

UNIFORM
HEAT INPUT
RATE,
.325 BTU/(HR-SQ FT)

.128 IN. THICK
6061-T6 ALUMINUM

27 DEG. R. HEAT EXCHANGER

LIQUID/VAPOR
INTERFACE
63.4 DEG. R.

LIQUID

VAPOR

63.8
63.7
63.5
63
62
61
60
59
57
53
49
45
41
37
33
31
29
28
29

63
62
61
60
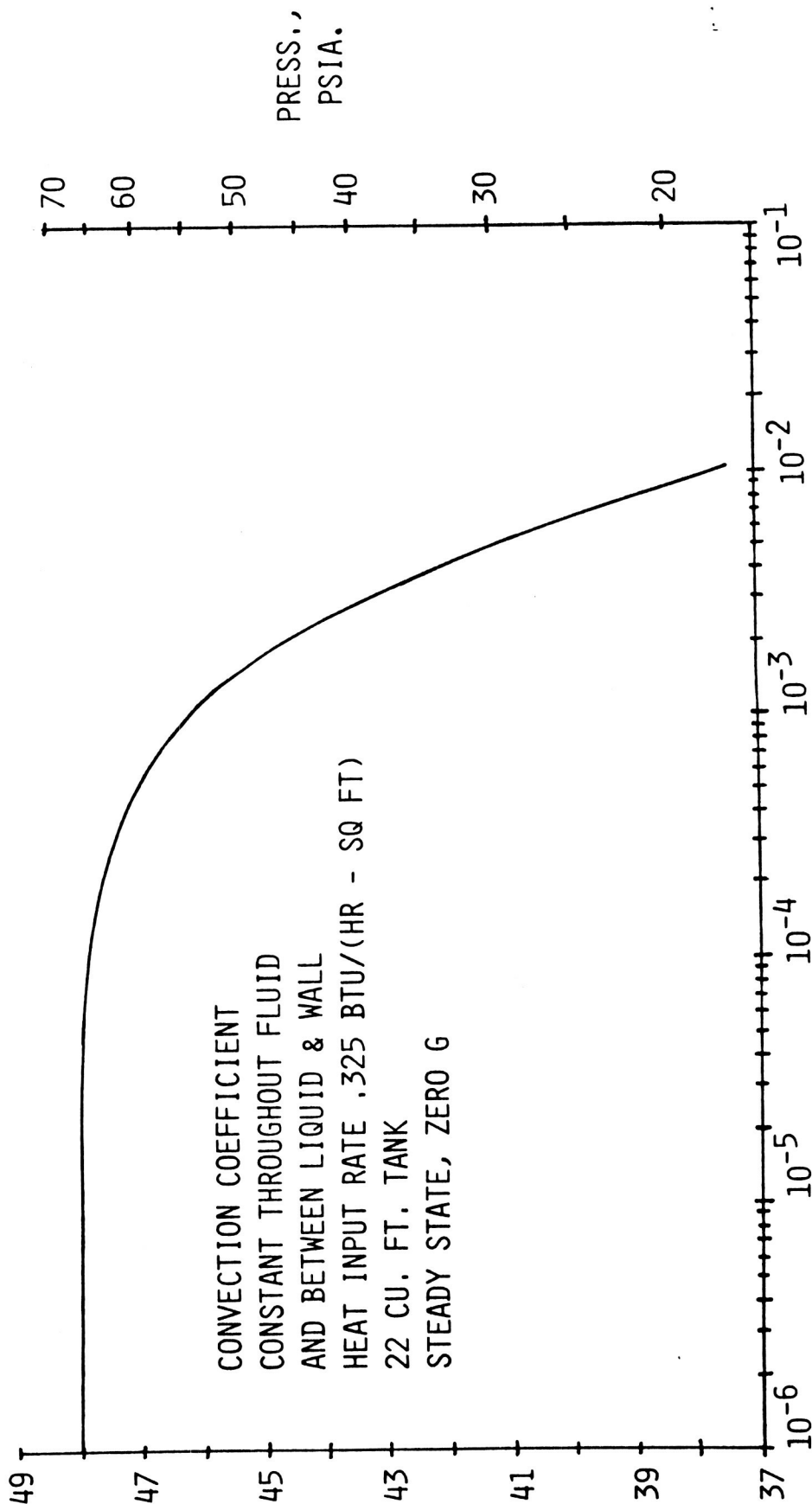59
57
53
49
45
41
37
35
31

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EFFECT OF CONVECTION ON LIQUID/VAPOR INTERFACE TEMPERATURE

o   WHAT LEVEL OF CONVECTION IS NECESSARY TO HAVE A SIGNIFICANT EFFECT ON
    TEMPERATURE DISTRIBUTION?

o   UNIFORM CONVECTION WAS ASSUMED THROUGHOUT THE FLUID AND BETWEEN THE LIQUID
    AND WALL

o   THE CONVECTION HEAT TRANSFER COEFFICIENT BECOMES SIGNIFICANT IN THE RANGE OF
    10E-04 TO 10E-03 BTU/(HR-SQ IN-DEG F) OR LARGER

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231

EFFECT OF CONVECTION ON LIQUID/VAPOR

INTERFACE TEMPERATURE & PRESSURE

LIQUID/
VAPOR
INTERFACE
TEMP.,
DEG. R.

PRESS.,
PSIA.

CONVECTION COEFFICIENT
CONSTANT THROUGHOUT FLUID
AND BETWEEN LIQUID & WALL
HEAT INPUT RATE .325 BTU/(HR - SQ FT)
22 CU. FT. TANK
STEADY STATE, ZERO G

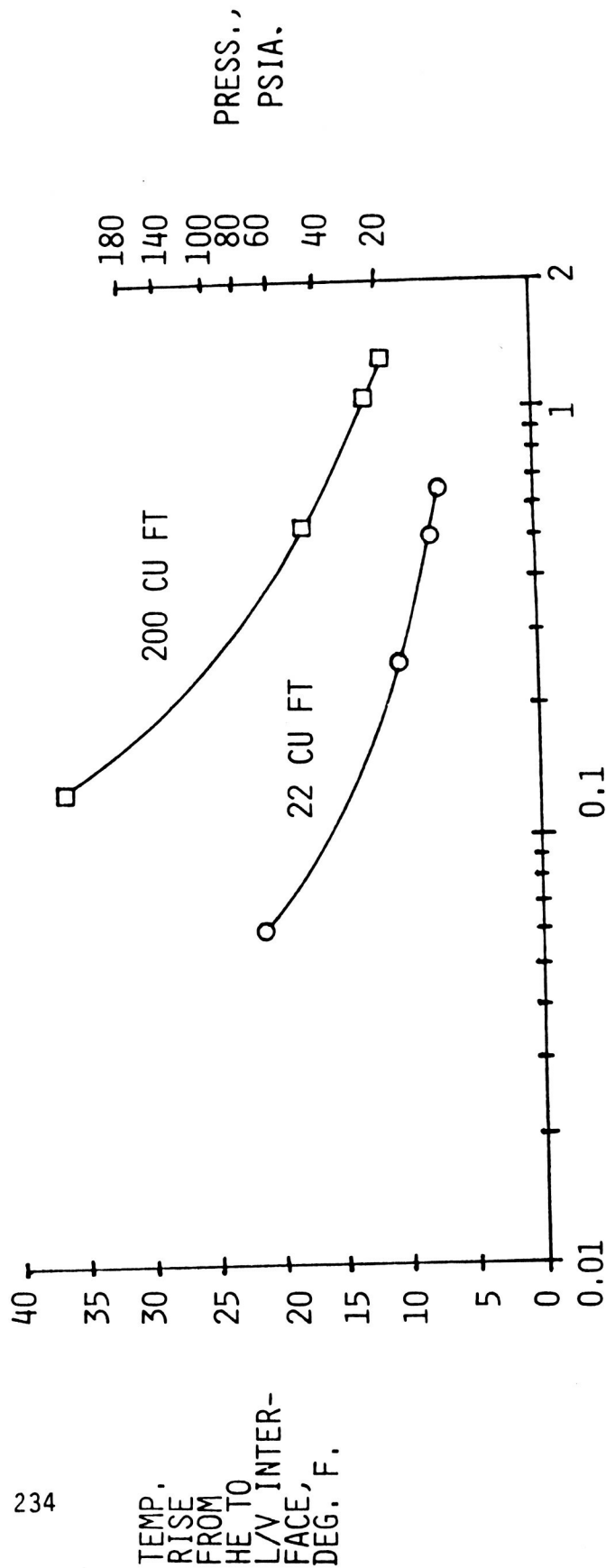CONVECTION HEAT TRANSFER COEFFICIENT
BTU/(HR-SQ. IN. - DEG. F.)

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EFFECT OF WALL THICKNESS ON LIQUID/VAPOR INTERFACE TEMPERATURE

LARGE TANKS DEVELOP STEADY STATE TEMPERATURES AND PRESSURES MUCH HIGHER THAN SMALL TANKS FOR THE SAME WALL THICKNESS AND HEAT TRANSFER RATE THROUGH THE TANK WALL

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EFFECT OF WALL THICKNESS ON
LIQUID/VAPOR INTERFACE TEMPERATURE

STEADY STATE, ZERO G
NO CONVECTION
HEAT INPUT RATE .325 BTU/(HR-SQ FT)

200 CU FT

22 CU FT

PRESS.,
PSIA.

180
140
100
80
60

40

20

2

1

0.1

WALL THICKNESS, INCHES

40

35

30

25

20

15

10

5

0

0.01

TEMP.
RISE
FROM
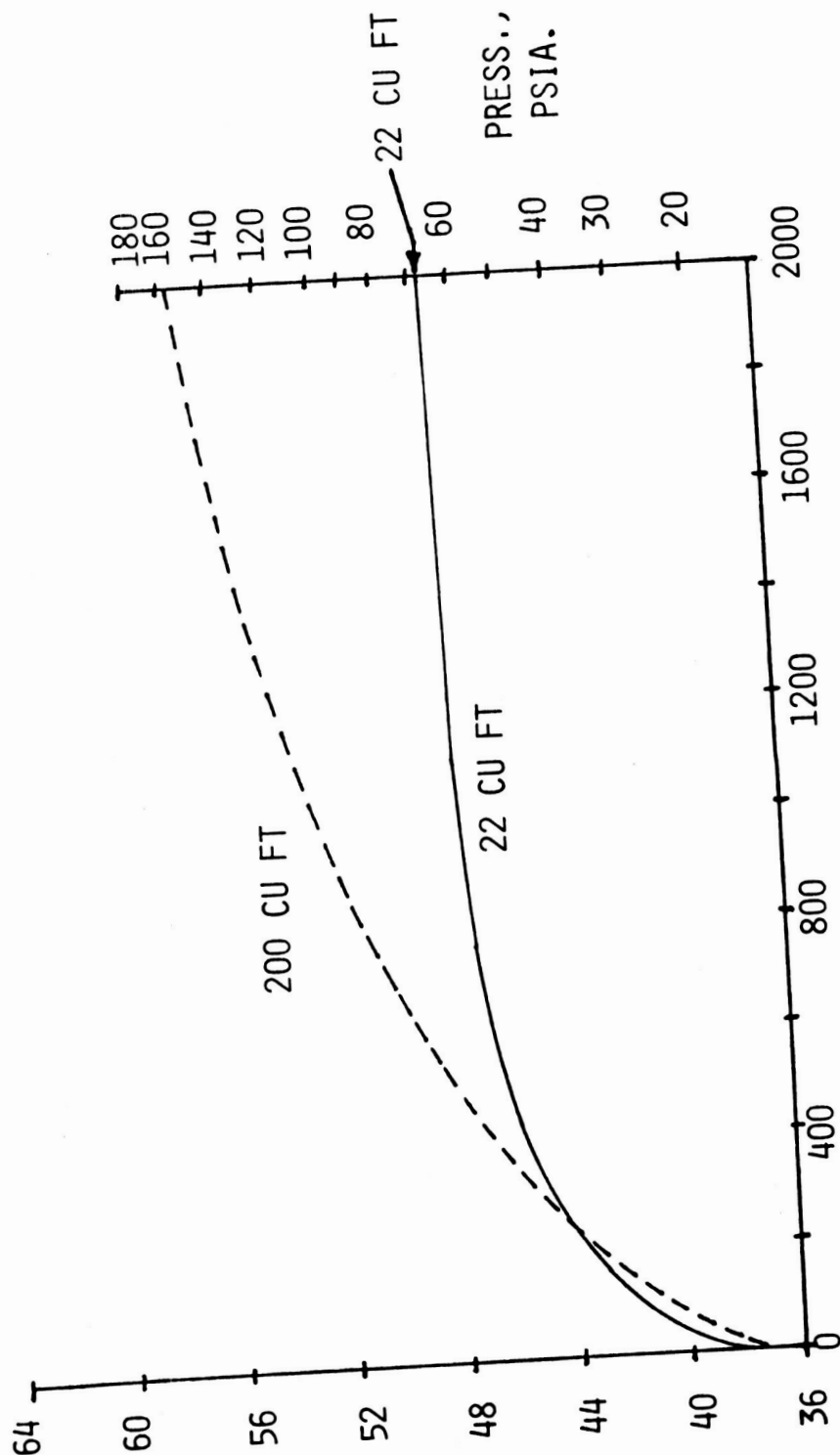HE TO
L/V INTER-
FACE, DEG. F.

234

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LIQUID/VAPOR INTERFACE TEMPERATURE VERSUS TIME

o   BOTH THE SMALL AND LARGE TANKS REQUIRE HUNDREDS OF HOURS TO REACH EVEN 60 PSIA

o   IN ABOUT 1000 HOURS THE SMALL TANK IS CLOSE TO EQUILIBRIUM

o   THE LARGE TANK REQUIRES MANY THOUSANDS OF HOURS TO REACH EQUILIBRIUM

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LIQUID/VAPOR INTERFACE
TEMPERATURE VERSUS TIME

STEADY
STATE

200 CU FT

22 CU FT

PRESS.,
PSIA.

200 CU FT

22 CU FT

TIME, HOURS

LIQUID/
VAPOR
INTER-
FACE
TEMP., °R.

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CONCLUSIONS

o CONDUCTION PROCESSES ARE VERY SLOW IN THE FLUID

o FOR SMALL TANKS, AN INTERNAL HEAT EXCHANGER IS EFFECTIVE IN CONTROLLING MAXIMUM TANK TEMPERATURE/PRESSURE

o THE FLUID CONVECTION COEFFICIENT MUST BE OF THE ORDER OF 10E-04 BTU/HR-SQ IN-DEG F OR LARGER TO CAUSE A DECREASE IN THE LIQUID/VAPOR INTERFACE TEMPERATURE

o INTERNAL CONVECTION (WITH A MIXER, FOR EXAMPLE) IS NECESSARY TO KEEP TANK PRESSURE LOW, ESPECIALLY IN LARGE VOLUME TANKS

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John Schuster/General Dynamics Space Systems:

The considerations on thermal mixing that you've done have been primarily limited to tanks nearly filled with liquid with a relatively small vapor ullage. Have you studied the opposite situation where you have mainly vapor in the tank and you are concerned about how that vapor will equilibrate with the liquid, and what the evaporation rate might be out of the liquid?

Smolak:

No, I didn't go into that. The model assumes that there is a constant temperature at the liquid vapor interface. The model at this point does not include evaporation at the liquid vapor interface, that part of the thermodynamics is not in there. The conduction processes and convection processes in the vapor were included when I did include convection. That part of it is rigorous, but that is as far as the thermodynamics went. It is not truly a complete thermodynamic model by any means.

A. A. Sonin/Massachusetts Institute of Technology:

I wonder if you could elaborate on how you applied the convective heat transfer coefficient, and what the boundary conditions were on your analysis when you did that?

Smolak:

I said that I had a heat transfer coefficient of the values that were stated. The area over which that convective coefficient was active was the area between adjacent nodes in the SINDA model and the appropriate temperature difference was the temperature difference between the adjacent nodes. In other words, it was put in as a HA-Delta-T type effect. It was not done with any directionality or preferentially; in other words, it was done between all adjacent surfaces. If there is better information on how convection acts in reduced gravity, I would be happy to put it into the model, but I couldn't find anything better in the literature.

Robert Rudlin/Martin Marietta Denver Aerospace:

I want to ask a question, but I observed one thing in your analysis which I think was very good. First, you do have to know what the convection coefficient or the Nusselt number is. I didn't pick up what the Nusselt number was, but I did pick up that your spacial dimensions from the free surface down to the heat exchanger at 27 degrees, which I guess is about 3 feet, is probably your biggest resistor, or the primary conductor. If I draw these conclusions correctly, it seems to me what your saying is when you doubled everything you basically doubled that 3 feet to 6 feet, and, sure enough, your temperature difference went from 30 degrees to 60 degrees. That's pretty much like you'd expect with a resistor/conductor model. Am I drawing the right conclusions in saying that what you're really telling me is that you have to have your heat exchanger on the wall and uniformly distributed through the fluid in order to keep that basic dimension significantly less than 3 feet if you want to have a fairly well mixed fluid? In other words, don't stir it up; just get your resistance path as small as possible, if you really want to control the temperature.

Smolak:

That's a long question. I would say yes, your supposition is pretty much valid. The scaling was done from the small tank to the larger tank and the results were not entirely unexpected. We did some more work that I didn't mention that had to do with placing a heat exchanger on what amounted to the north pole in the model, which was up near the vapor bubble. That was rather effective in helping to destroy these temperature gradients in the fluid. Yes, you are on the right track. We have not explored really extensively the optimum positions for those heat exchangers. What we had in mind was, since most of the tank penetration was toward the top of the tank, that we'd intercept the heat coming through those penetrations with a low temperature fluid from the visco jet or thermodynamic vent system and that seemed to be rather effective.