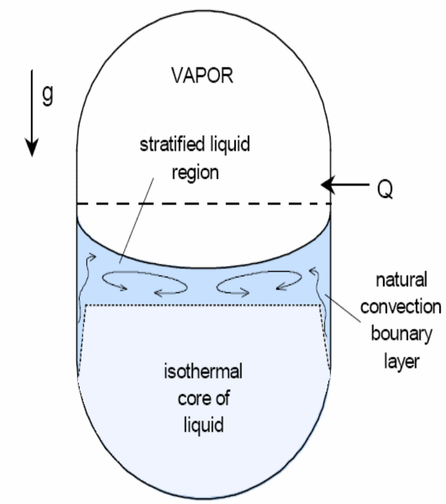
Upper Stage Tank Thermodynamic Modeling Using SINDA/FLUINT



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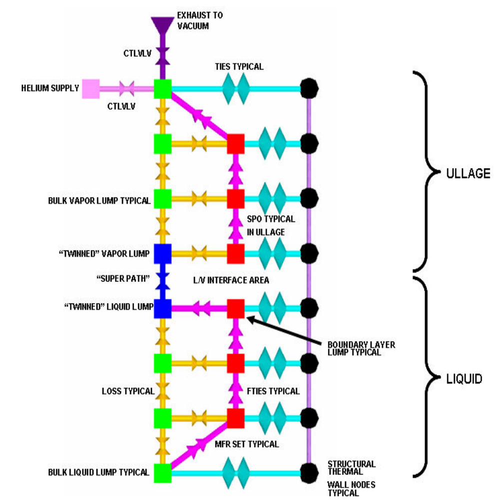


Outline

- Purpose/Overview
- Introduction
- Approach
- Fluid Sub-model Integration
- Required Inputs
- Stratification Modeling
- Rotation Modeling
- Slosh Modeling
- Conclusion

Purpose/Overview

The purpose of this work is:

- Provide an independent modeling capability within NASA's Launch Services Program for cryogenic upper stages

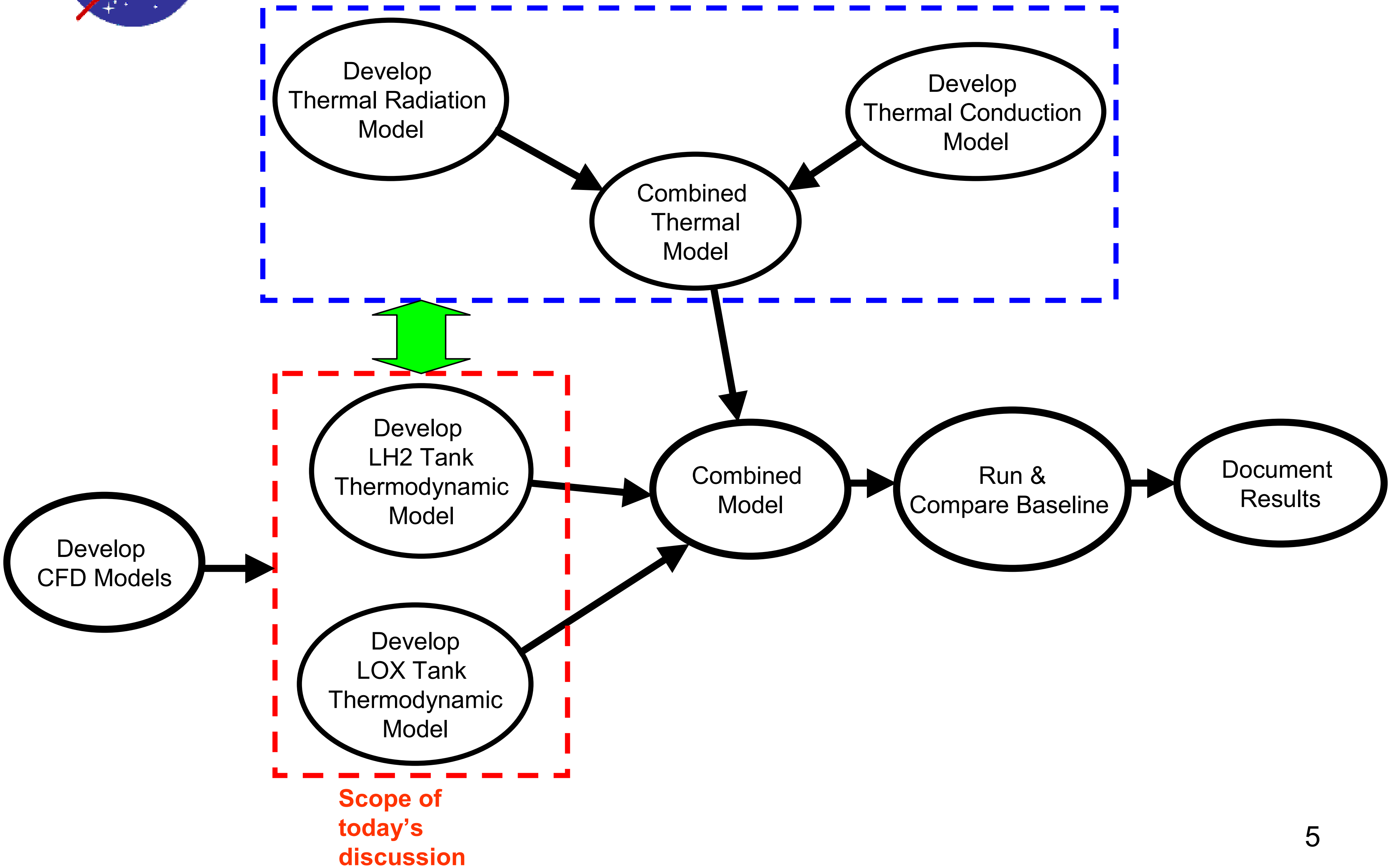
In this briefing, the following will be presented

- Describe the modeling approach employed
- Generic results to date

Introduction

- The NASA Launch Services Program’s Thermal/ Fluids team was tasked with developing a tool for future EELV mission IV&V activities
- This tool would allow for both thermal structural modeling as well as tank thermodynamics
- The desire to have a fully coupled thermal and fluids/thermodynamic modeling capability lead to the use of a commercially available software platform: SINDA/FLUINT
- The presentation specifically describes the fluids/thermodynamic modeling portion of the tool

Approach


Develop
Thermal Radiation
Model
Develop
Thermal Conduction
Model
Combined
Thermal
Model
Develop
LH2 Tank
Thermodynamic
Model
Develop
CFD Models
Develop
LOX Tank
Thermodynamic
Model
Combined
Model
Run &
Compare Baseline
Document
Results
Scope of
today's
discussion

Approach

- **Fluids/Thermodynamics Modeling – FLUINT**
  - Fluid Conduction
    - Stratification
  - Convection
    - B/L development
  - Mass Transfer
    - Diffusion, vaporization & condensation
  - Boiling
  - Pressurization & Venting
  - Liquid Vapor Interface Area/Liquid Wall Interface Area during Rotation

Fluid Sub-model Integration

- **Fluid to Structure Integration**
  - TIEs are used to couple the thermal and fluid models
    - Analogous to SINDA conductors
    - Fluint lump to SINDA node energy interchange
    - Heat transfer coefficient can be inputted manually or automatically calculated by the program
- **Transient Integration**
  - Utilized S/F build commands to engage and disengage individual fluid sub-models to simulate discrete "events" along a continuous timeline
    - **Stratification**
    - **Rotation**
    - **Slosh**
  - Sequencing of "events" is controlled in OPERATIONS block and is dependant upon
    - Knowledge of mission being simulated
    - Identification of environments that signify the "event"
    - Use of multiple definitions of simulation completion times
    - Identification of variables necessary to maintain continuity between "events"
  - Thermo model may be run independently from the thermal model

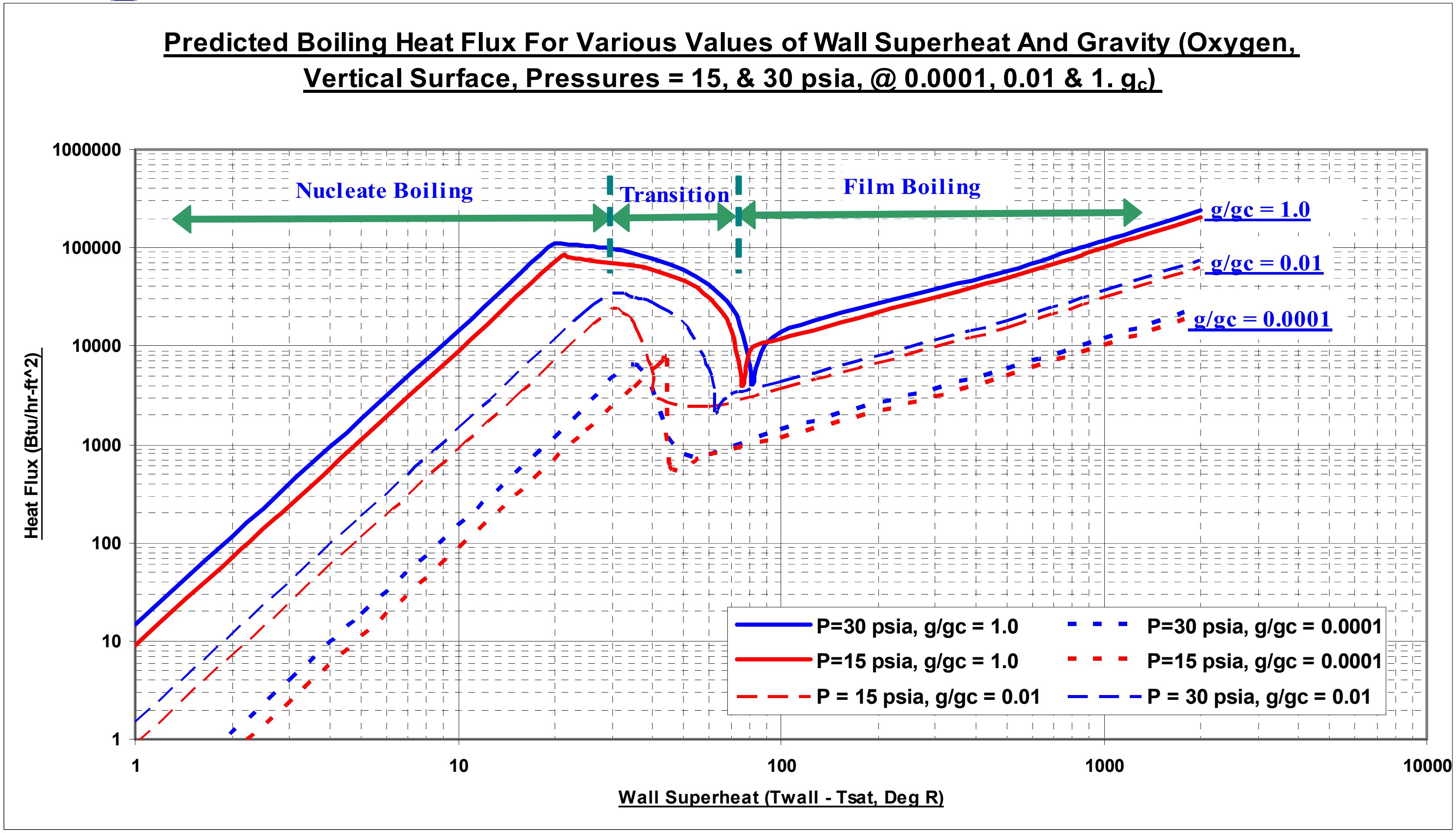
Required Inputs

- **Requires the input of various external data files**
  - Mission Variables
    - Gravity
    - Rate of rotation (Passive Thermal Control Roll)
    - Vent schedule
    - CFD data relevant to fluid location within tank
  - Sub-routine files
    - Fluid depth
    - Liquid/vapor interface area and liquid/tank interface area
    - Boundary layer development
    - Natural convection
    - Boiling

Basic Overview of S/F

- SINDA
  - Nodes - Thermal mass
  - Conductors - Structural conduction path
- FLUINT
  - Lumps/tanks - Homogeneous fluid @ P & T
  - Twinned tank - Non-homogeneous tank
  - Paths - Momentum and energy balance
- Uncommon use of FLUINT (network code) to model fluid volume

Boiling Subroutine

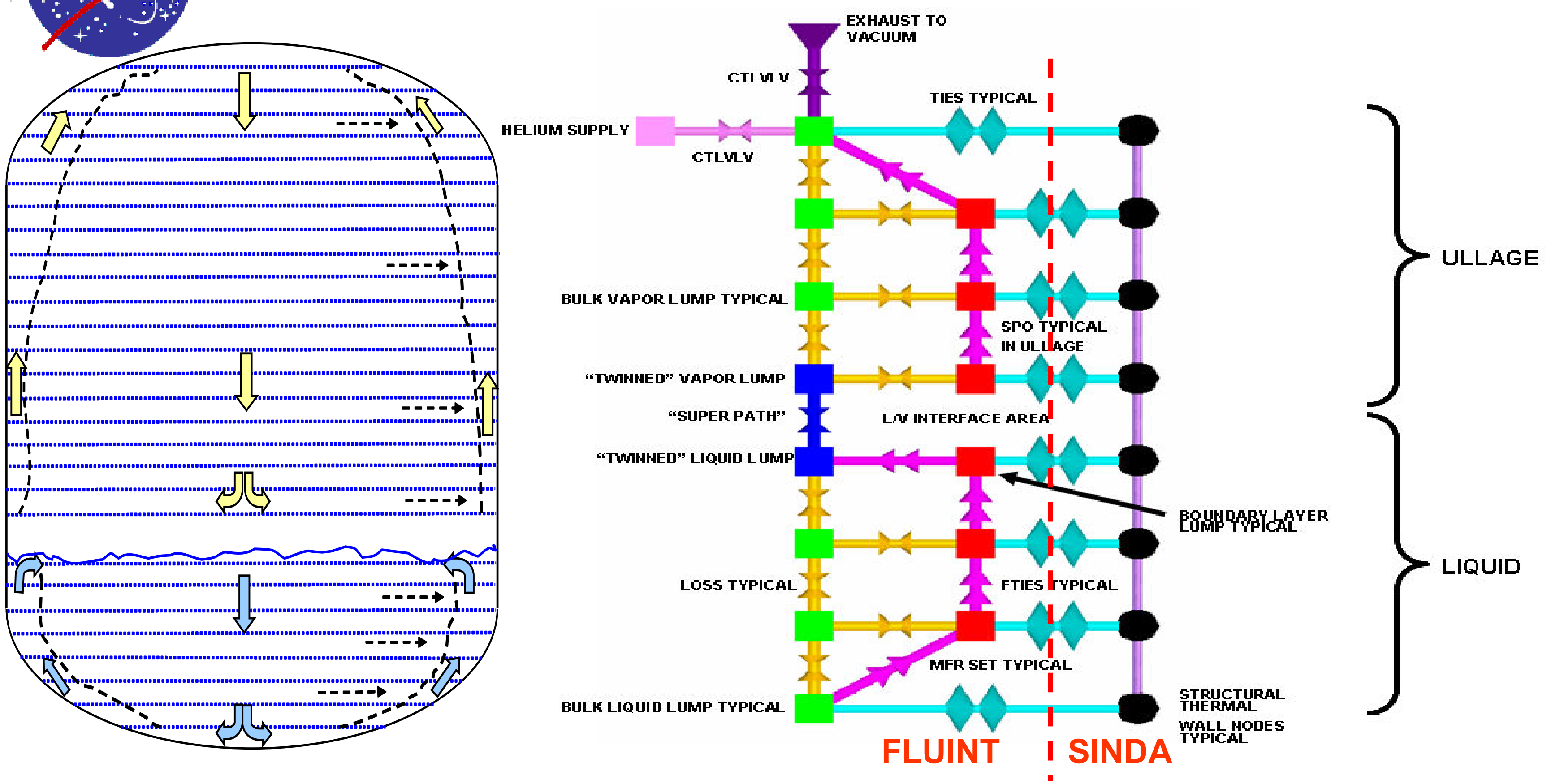


- All regimes of boiling and reduced gravity effects accounted for

Stratification – Event 1

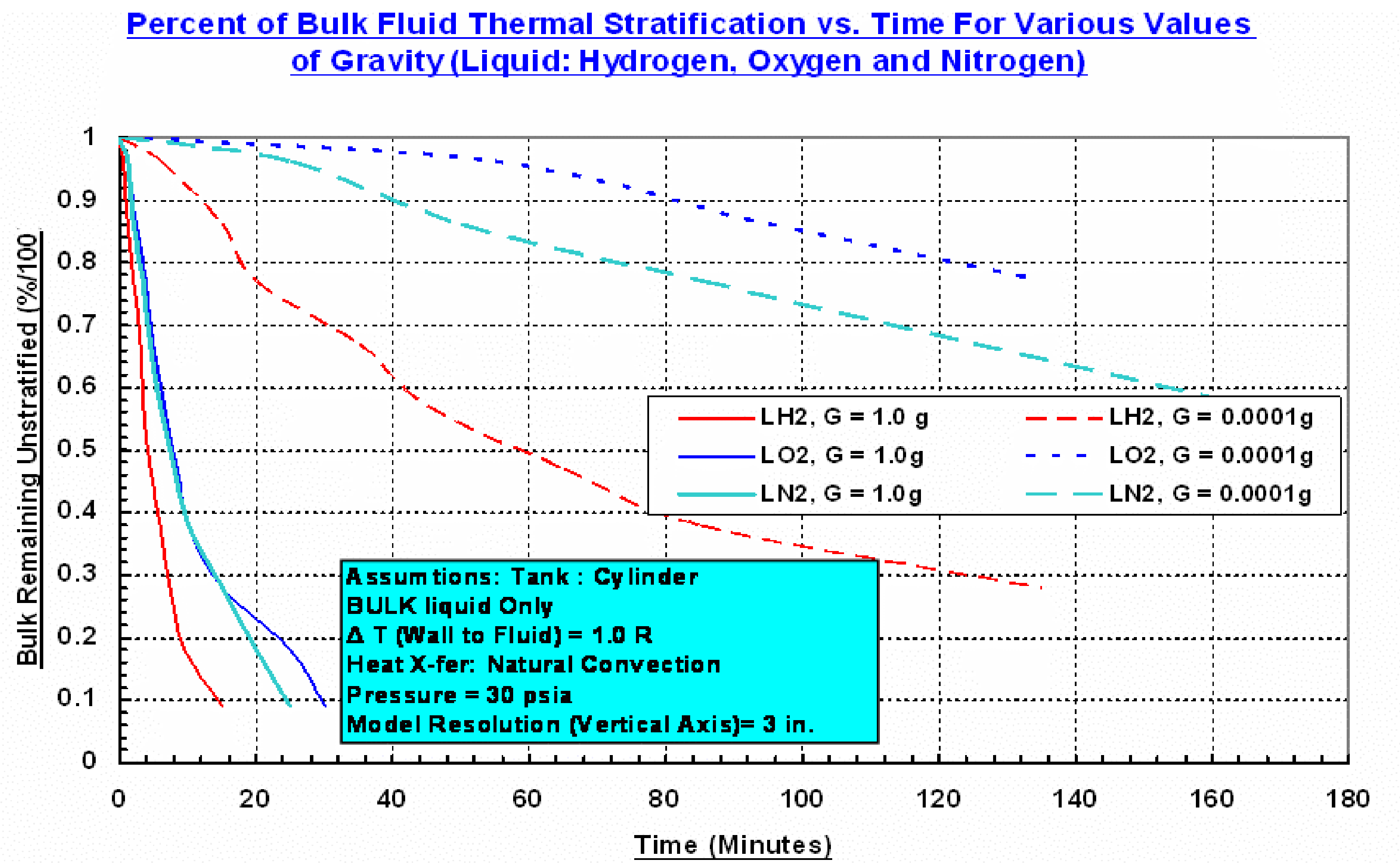
- Development of a temperature stratum within a fluid largely due to buoyancy driven forces
- Model needs to account for
  - Energy and mass transport
  - Exhibit sufficient resolution to capture stratification
  - [Number of axial layers left to the discretion of the modeler]
- Model designed to accept
  - A direct heat flux input into the thermal nodes
  - A temperature difference between the wall and fluid
  - TIE's coupling the fluid/thermo model directly with the thermal model
- Boundary layer subroutine provides
  - Local boundary layer thickness
  - Mass flow rates

Stratification (Continued)



- TIEs – Thermal to Fluids/Thermodynamic model coupler
- FTIEs – Fluid lump to lump conduction
- MFRSETs – Mass flow rate sets (calculated via boundary layer routine)
- LOSS – Generic two way fluid lump connector
- SPO – Connector for species specific diffusion in ullage
- SUPER PATH – handles mass transfer at liquid vapor interface
- CTLVLV – Used to control tank pressurization and depressurization

Stratification Results

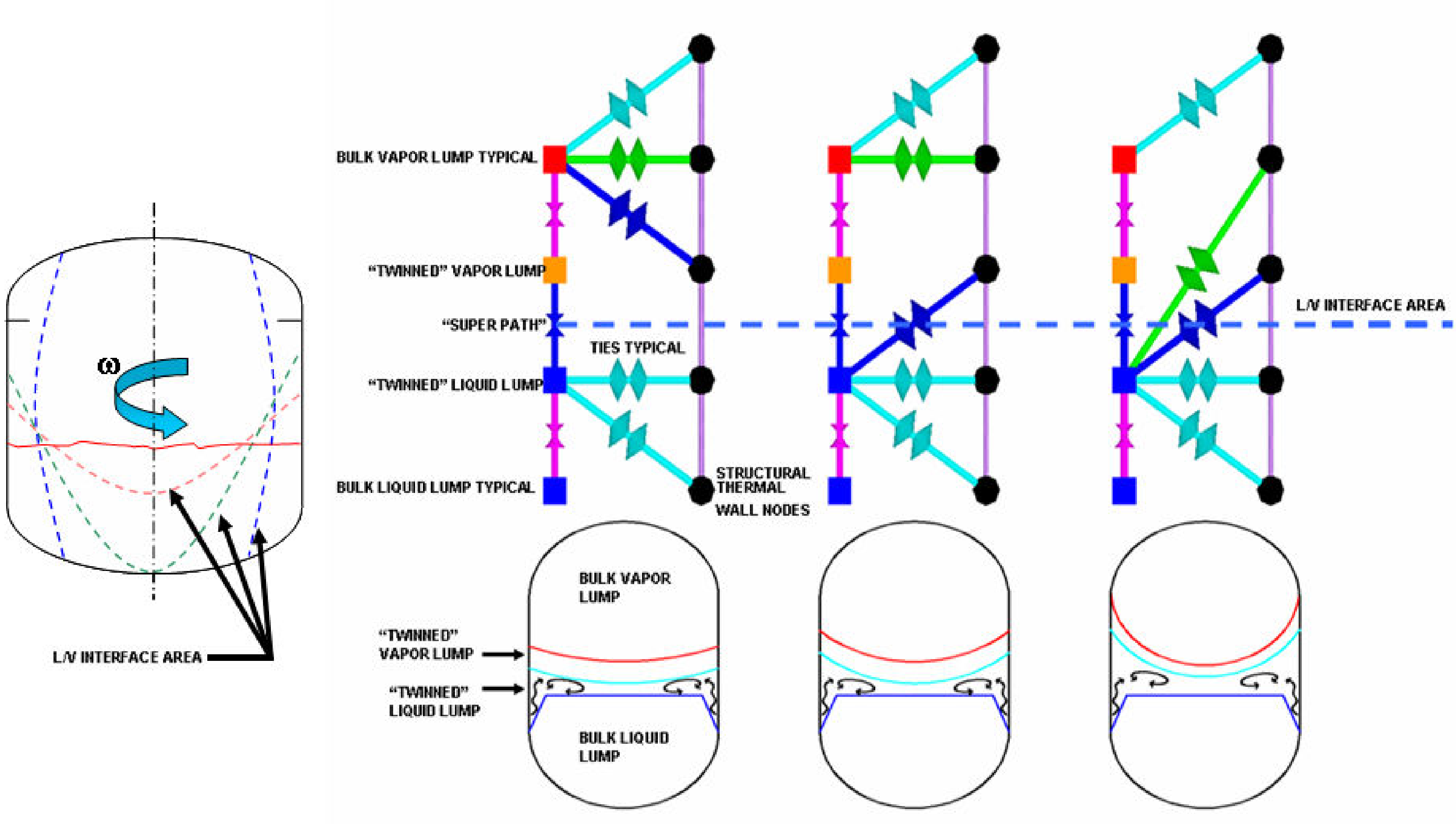


- Stratification was successfully modeled for various values of g
- Compared well to published data

Rotation – Event 2

- Development of the rotation model was motivated by the common occurrence of PTC roll in space/launch vehicles
- Model needs to account for
  - Proper liquid/wall interface area
  - Proper liquid/vapor interface area
  - Development of “warm layer” or stratum
  - Proper mixing within fluid and ullage lumps
- PUTTIE routine
  - Dynamically moves TIEs as fluid comes in contact with hot wall areas
- Boiling subroutine
  - Accounts for any occurrence of boiling as the fluid comes into contact with hot walls that were previously adjacent to the ullage
- Data arrays provide a data base to determine liquid height and liquid/vapor interface area
  - Fill %
  - Rate of rotation (deg/s)
  - Gravity ratio (g/g_c)
  - Data conforms to inputs provided by CFD simulations

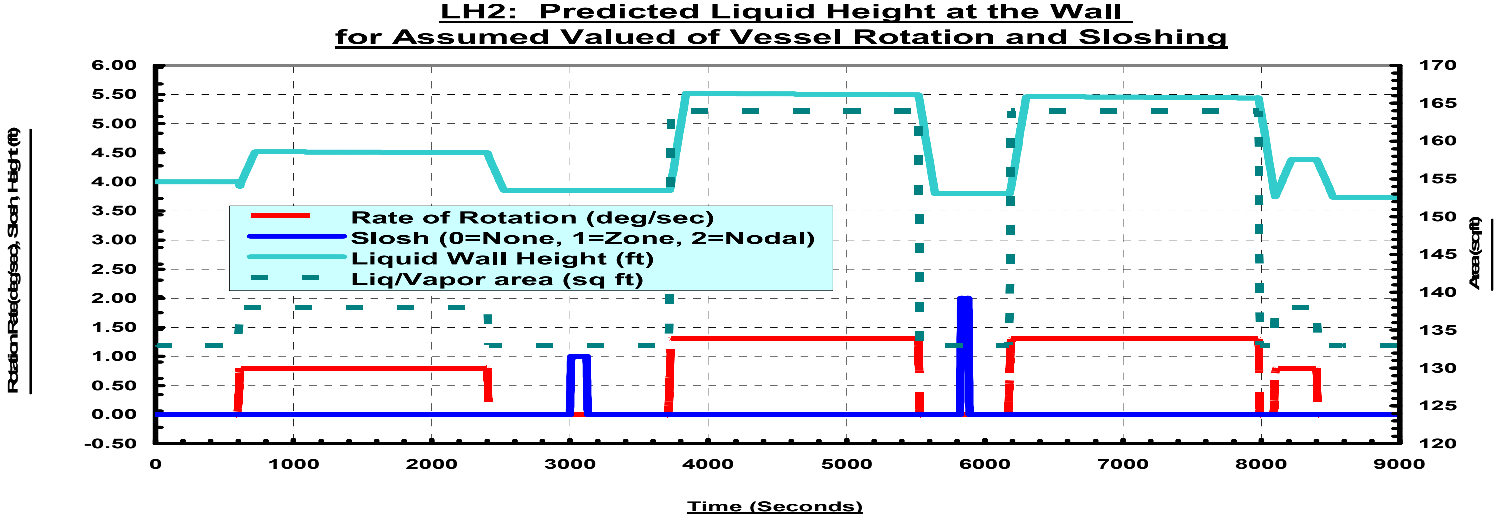
Rotation (Continued)

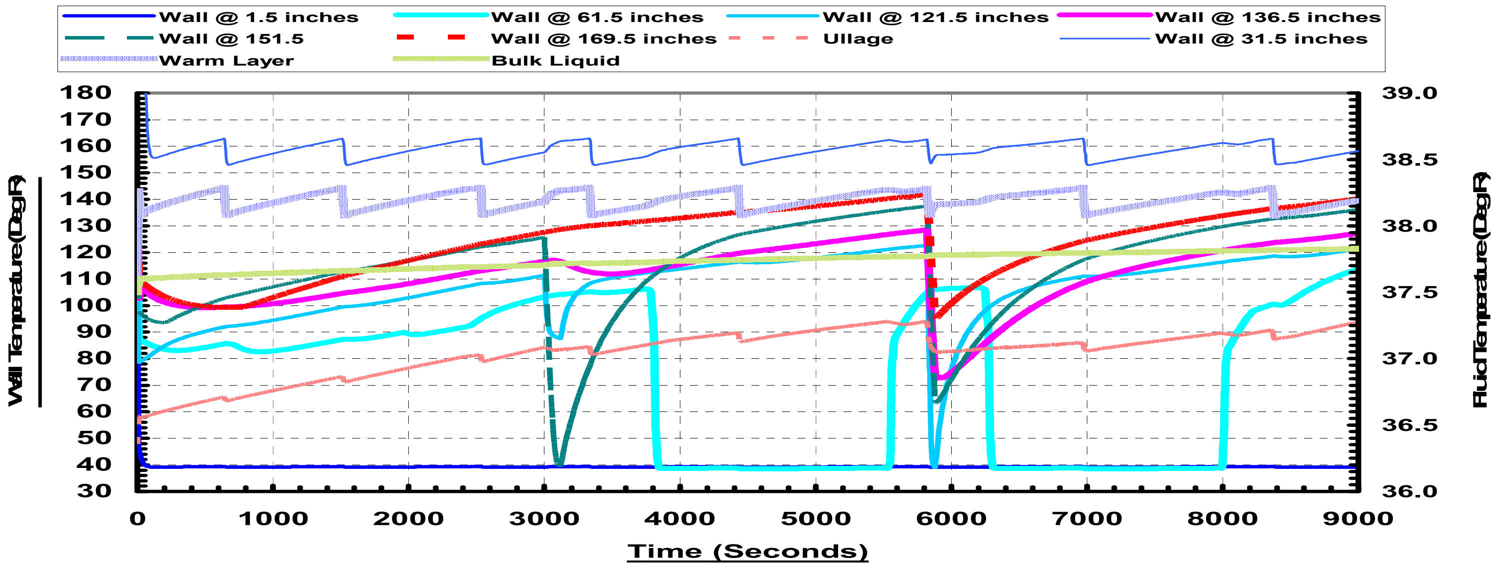


- PUTIE routine dynamically moves the tie to the appropriate adjacent fluid or vapor lump as the fluid moves up the wall during a rotation event

Rotation Results (Cont.)

LAUNCH SERVICES PROGRAM





Disclaimer: This package is part of an oral presentation of the following paper: AIAA-2006-5051. Information contained herein is only to be used in conjunction with the aforementioned oral presentation.

Slosh – Event 3

- Development of the slosh model was motivated by the interest in potential effect on tank pressure (ullage collapse) and liquid boil-off
- Slosh fluid network is very similar to the rotation event
- The chaotic nature of the event precludes a high fidelity model
- Slosh also utilizes the PUTTIE routine
- Boiling subroutine
- Two levels of fidelity available to user
  - Zone (clusters of SINDA nodes) wetting
  - Individual SINDA node wetting
- CFD analysis provides intelligent input for conjugate modeling

Slosh (Continued)

8 radial, 56 vertical segments

56	DOME	21000	155	21001	255	21002	355	21003	455	21004	555	21005	655	21006	755	21007	855	1
55	DOME	20800	154	20801	254	20802	354	20803	454	20804	554	20805	654	20806	754	20807	854	2
54	DOME	20600	153	20601	253	30 20602	353	20603	453	20604	553	20605	653	32 20606	753	20607	853	3
53	DOME	29 20400	152	20401	252	20402	352	20403	452	31 20404	552	20405	652	20406	752	20407	852	4
52	DOME	20200	151	20201	251	20202	351	20203	451	20204	551	20205	651	20206	751	20207	851	5
51	DOME	20000	150	20001	250	20002	350	20003	450	20004	550	20005	650	20006	750	20007	850	6
50	DOME	19800	149	19801	249	19802	349	19803	449	19804	549	19805	649	19806	749	19807	849	7
49	DOME	19600	148	19601	248	19602	348	19603	448	19604	548	19605	648	19606	748	19607	848	8
48	DOME	19400	147	19401	247	19402	347	19403	447	19404	547	19405	647	19406	747	19407	847	9
47	DOME	19200	146	19201	246	19202	346	19203	446	19204	546	19205	646	19206	746	19207	846	10
46	DOME	25 19000	145	19001	245	26 19002	345	19003	445	27 19004	545	19005	645	28 19006	745	19007	845	11
45	DOME	18800	144	18801	244	18802	344	18803	444	18804	544	18805	644	18806	744	18807	844	12
44	DOME	18600	143	18601	243	18602	343	18603	443	18604	543	18605	643	18606	743	18607	843	13
43	DOME	18400	142	18401	242	18402	342	18403	442	18404	542	18405	642	18406	742	18407	842	14
42	DOME	18200	141	18201	241	18202	341	18203	441	18204	541	18205	641	18206	741	18207	841	15
41	DOME	18000	140	18001	240	18002	340	18003	440	18004	540	18005	640	18006	740	18007	840	16
40	DOME	17800	139	17801	239	17802	339	17803	439	17804	539	17805	639	17806	739	17807	839	17
39	DOME	21 17600	138	17601	238	22 17602	338	17603	438	23 17604	538	17605	638	24 17606	738	17607	838	18
38	DOME	17400	137	17401	237	17402	337	17403	437	17404	537	17405	637	17406	737	17407	837	19
37	DOME	17200	136	17201	236	17202	336	17203	436	17204	536	17205	636	17206	736	17207	836	20
36	DOME	17000	135	17001	235	17002	335	17003	435	17004	535	17005	635	17006	735	17007	835	21
35	CYLINDER	16800	134	16801	234	16802	334	16803	434	16804	534	16805	634	16806	734	16807	834	1
34	CYLINDER	16600	133	16601	233	16602	333	16603	433	16604	533	16605	633	16606	733	16607	833	2
33	CYLINDER	17 16400	132	16401	232	16402	332	16403	432	19 16404	532	16405	632	20 16406	732	16407	832	3
		22100		22101		18 22102		22103		22104		22105		22106		22107		
32	CYLINDER	16200	131	16201	231	16202	331	16203	431	16204	531	16205	631	16206	731	16207	831	4
31	CYLINDER	16000	130	16001	230	16002	330	16003	430	16004	530	16005	630	16006	730	16007	830	5
30	CYLINDER	15800	129	15801	229	15802	329	15803	429	15804	529	15805	629	15806	729	15807	829	6
29	CYLINDER	15600	128	15601	228	15602	328	15603	428	15604	528	15605	628	15606	728	15607	828	7
28	CYLINDER	15400	127	15401	227	15402	327	15403	427	15404	527	15405	627	15406	727	15407	827	8
27	CYLINDER	15200	126	15201	226	15202	326	15203	426	15204	526	15205	626	15206	726	15207	826	9
26	CYLINDER	15000	125	15001	225	15002	325	15003	425	15004	525	15005	625	15006	725	15007	825	10
25	CYLINDER	13 14800	124	14801	224	14 14802	324	14803	424	15 14804	524	14805	624	16 14806	724	14807	824	11
24	CYLINDER	14600	123	14601	223	14602	323	14603	423	14604	523	14605	623	14606	723	14607	823	12
23	CYLINDER	14400	122	14401	222	14402	322	14403	422	14404	522	14405	622	14406	722	14407	822	13
22	CYLINDER	14200	121	14201	221	14202	321	14203	421	14204	521	14205	621	14206	721	14207	821	14
21	DOME	14000	120	14001	220	14002	320	14003	420	14004	520	14005	620	14006	720	14007	820	1
20	DOME	13800	119	13801	219	13802	319	13803	419	13804	519	13805	619	13806	719	13807	819	2
19	DOME	13600	118	13601	218	13602	318	13603	418	13604	518	13605	618	13606	718	13607	818	3
18	DOME	9 13400	117	13401	217	10 13402	317	13403	417	11 13404	517	13405	617	12 13406	717	13407	817	4
17	DOME	13200	116	13201	216	13202	316	13203	416	13204	516	13205	616	13206	716	13207	816	5
16	DOME	13000	115	13001	215	13002	315	13003	415	13004	515	13005	615	13006	715	13007	815	6
15	DOME	12800	114	12801	214	12802	314	12803	414	12804	514	12805	614	12806	714	12807	814	7
14	DOME	12600	113	12601	213	12602	313	12603	413	12604	513	12605	613	12606	713	12607	813	8
13	DOME	12400	112	12401	212	12402	312	12403	412	12404	512	12405	612	12406	712	12407	812	9
12	DOME	12200	111	12201	211	12202	311	12203	411	12204	511	12205	611	12206	711	12207	811	10
11	DOME	5 12000	110	12001	210	6 12002	310	12003	410	7 12004	510	12005	610	8 12006	710	12007	810	11
10	DOME	11800	109	11801	209	11802	309	11803	409	11804	509	11805	609	11806	709	11807	809	12
9	DOME	11600	108	11601	208	11602	308	11603	408	11604	508	11605	608	11606	708	11607	808	13
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7	DOME	11200	106	11201	206	11202	306	11203	406	11204	506	11205	606	11206	706	11207	806	15
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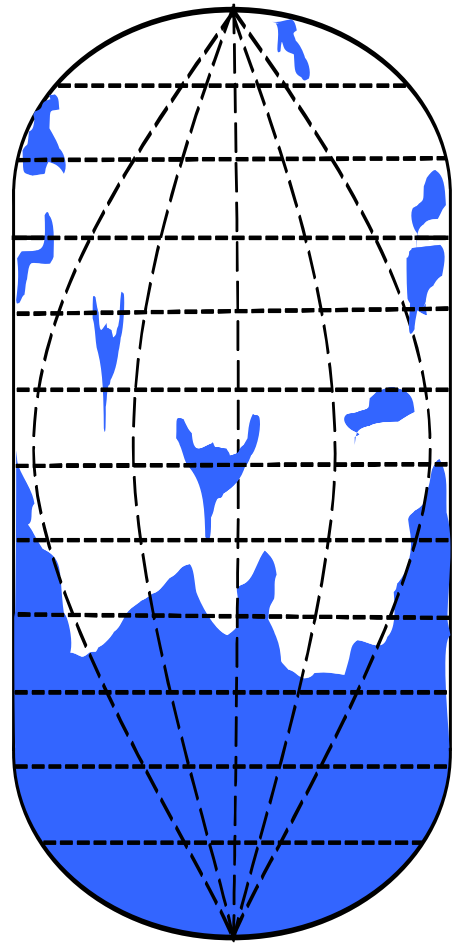
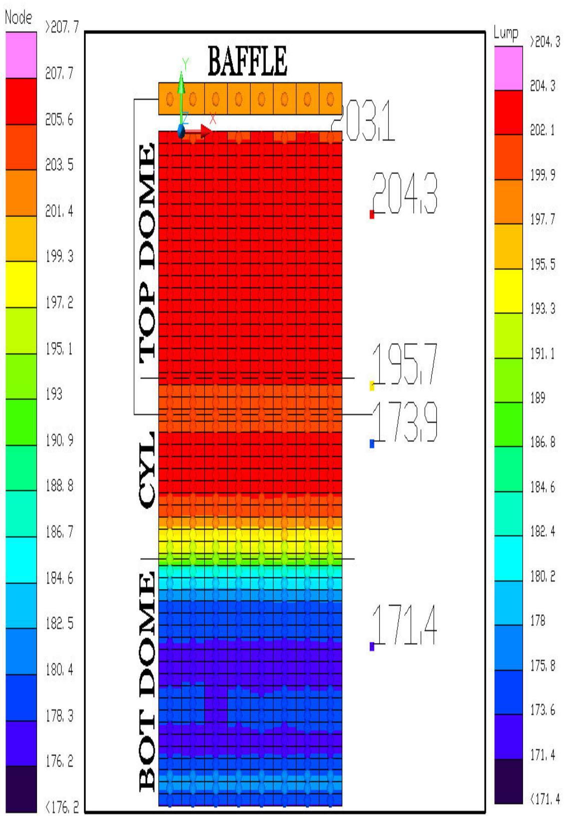
5	DOME	10800	104	10801	204	10802	304	10803	404	10804	504	10805	604	10806	704	10807	804	17
4	DOME	1 10600	103	10601	203	2 10602	303	10603	403	3 10604	503	10605	603	4 10606	703	10607	803	18
3	DOME	10400	102	10401	202	10402	302	10403	402	10404	502	10405	602	10406	702	10407	802	19
2	DOME	10200	101	10201	201	10202	301	10203	401	10204	501	10205	601	10206	701	10207	801	20
1	DOME	10000	100	10001	200	10002	300	10003	400	10004	500	10005	600	10006	700	10007	800	21
	FIRST	1000		200		300		400		500		600		700		800		BOTTOM
	LAST	1056		256		356		456		556		656		756		856		TOP

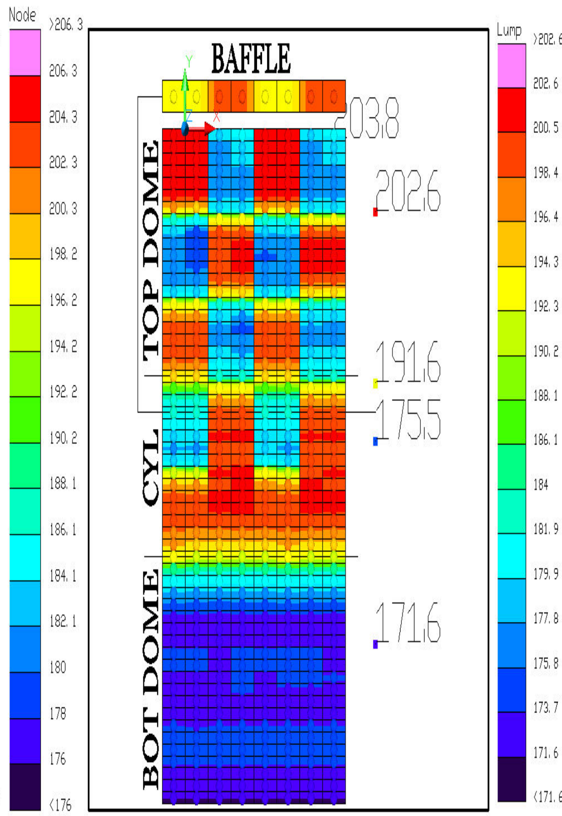


- Tank Nodal breakdown can also be clustered into zones (white/green) for the slosh routine

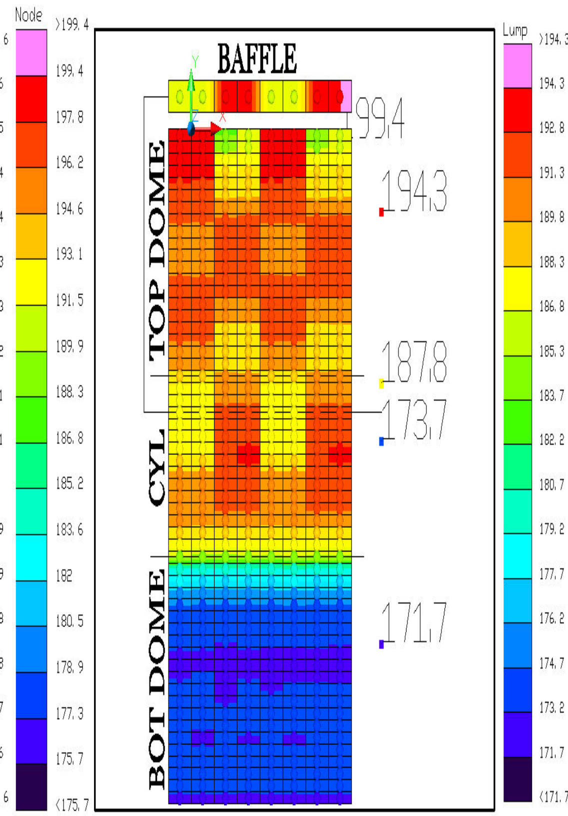
Slosh Results – Zone Slosh



BEFORE SLOSH EVENT



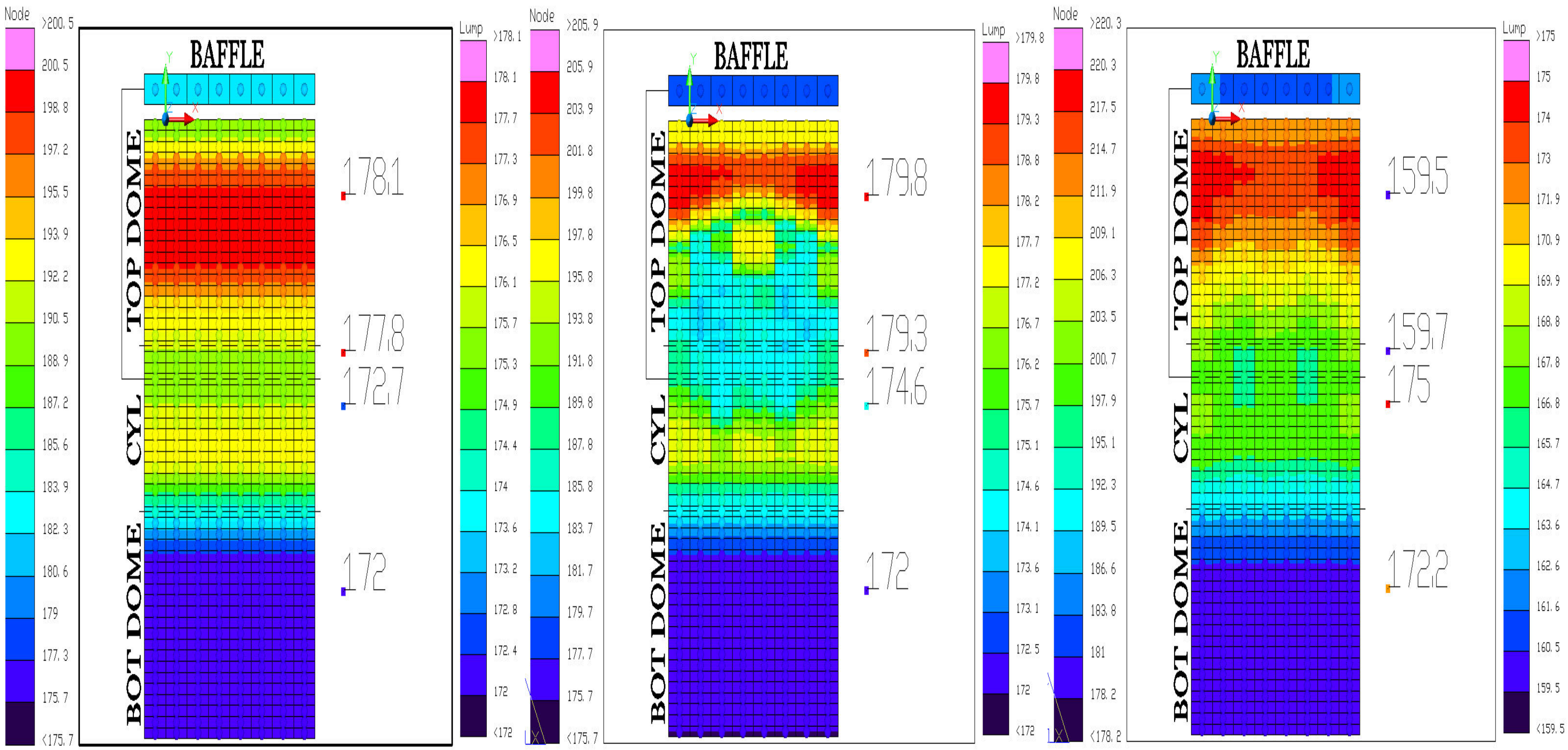
DURING SLOSH EVENT



AFTER SLOSH EVENT

- TIES stay connected to thermal node. They switch from liquid to ullage and vise versa

Slosh Results – Node Slosh



BEFORE SLOSH EVENT

DURING SLOSH EVENT

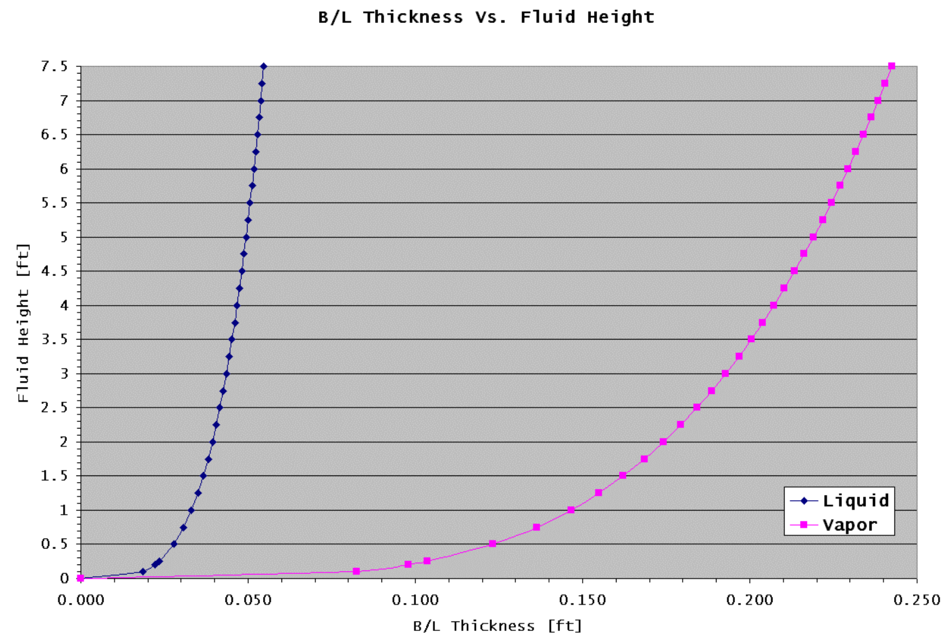
AFTER SLOSH EVENT

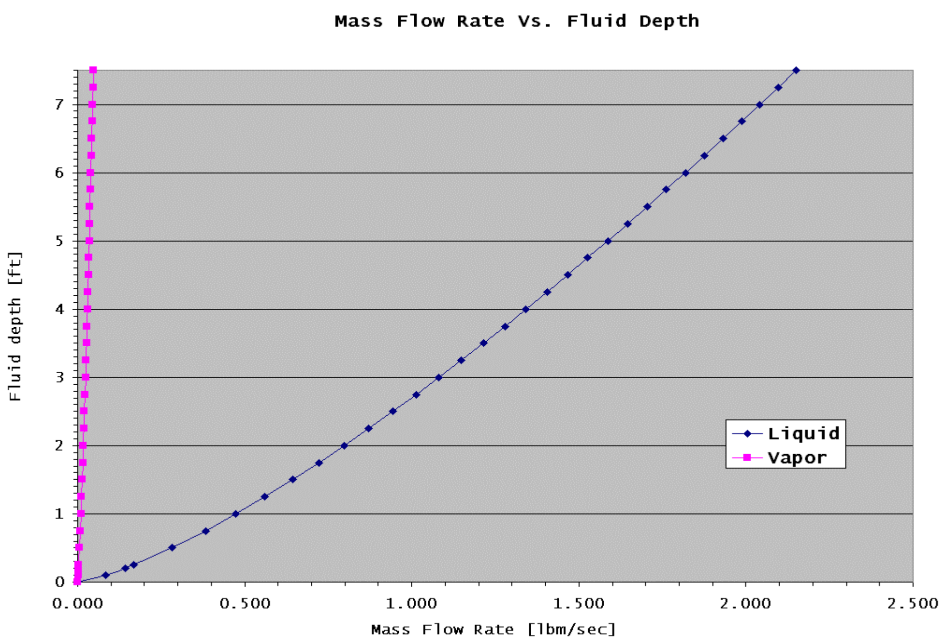
Conclusion

- Tool has been successfully developed for use in predicting upper stage propellant thermodynamics
- Achieved full thermal-fluids coupling using commercially available SINDA/FLUINT
- Event models can run concurrently
- The tool set will form a foundation for future NASA LSP analysis efforts
- The suite can be easily adapted for
  - EELVS fleet
  - CLV, CaLV and CEV
  - Commercial applications (any fluid, any tank)

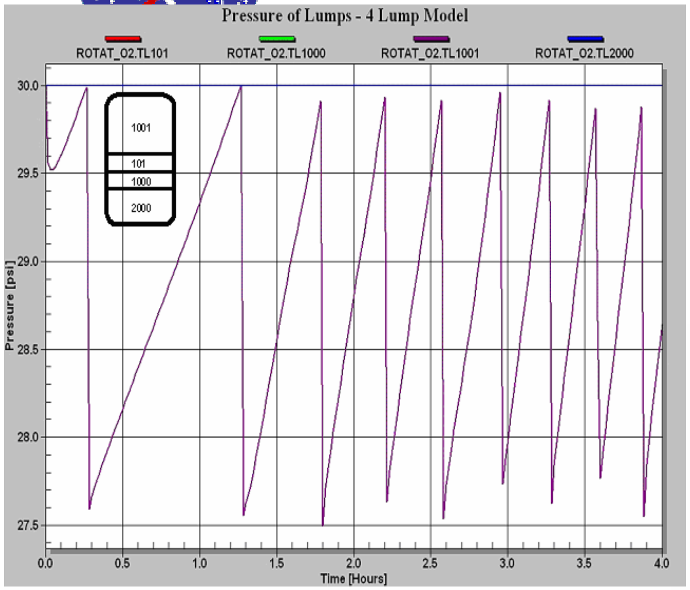
Questions?

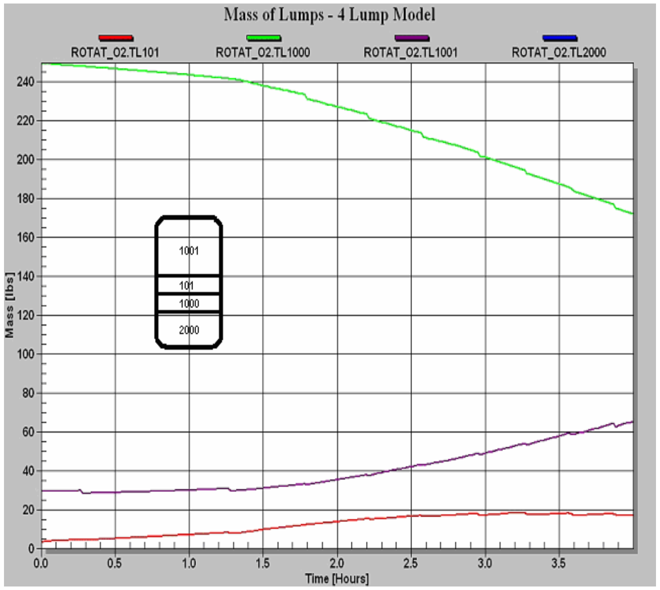
Boundary Layer Development Results

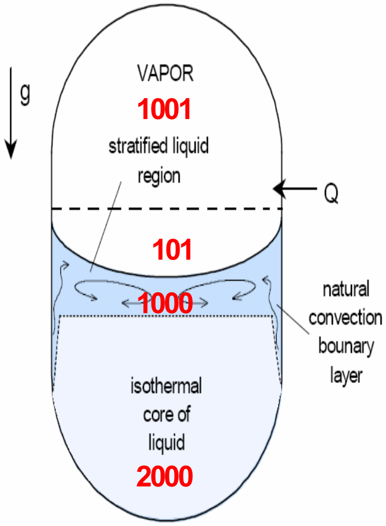


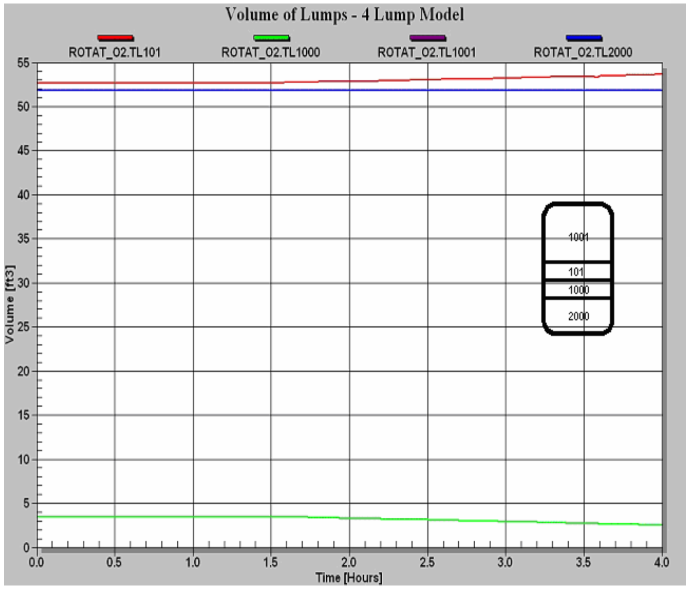


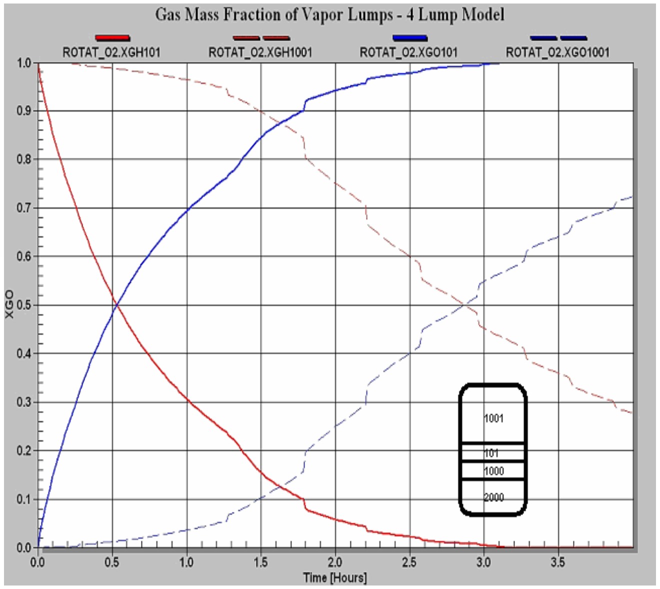
Modeling with Twinned Tanks











Rotation Results (Cont.)

Assumed Conditions: 20% of available dry wall is splashed at slosh, $g/g_C = 10^{-4}$
Period = 2.5 Hours, 1400 lbs liquid, Tank Fill Level ≈ 22% (Full = 1496 cu. Ft.)
Initial Conditions: Wall Temperature = Sat + 100 °R,
P = 19 psia, Liquid Temperature = 37.5 °R, Ullage Temperature = Sat +10 °R