

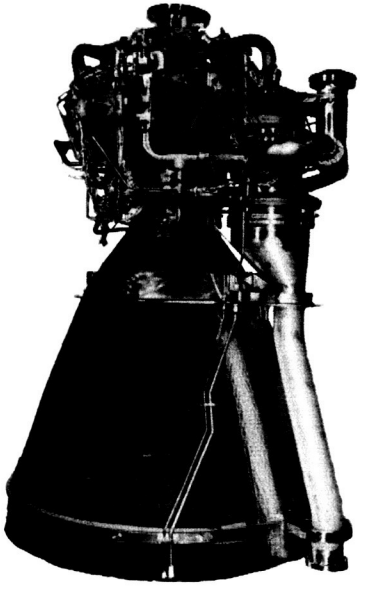
MSFC Turbomachinery Fluid Dynamics Roadmap

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Turbomachinery Fluid Dynamics - Team Objective

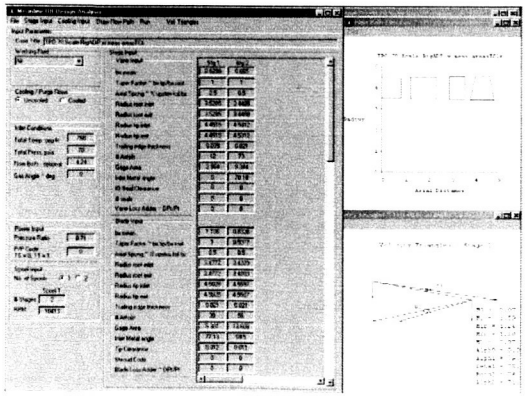
To expand the knowledge and understanding of the fluid dynamics of turbomachinery and to use that knowledge and understanding to improve the performance, reliability, and robustness of turbomachinery hardware

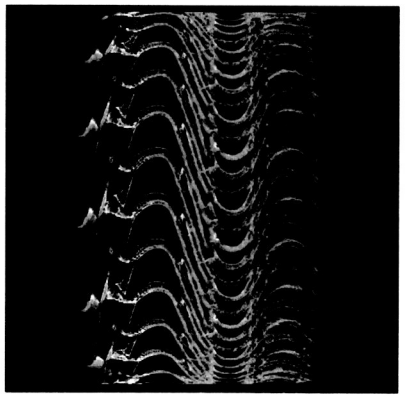


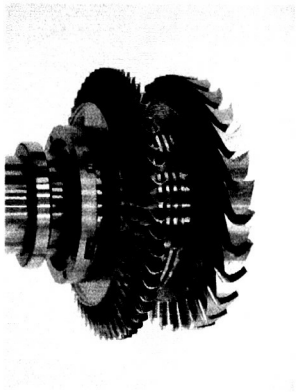
Approach



- Develop and enhance aerodynamic and hydrodynamic design tools and CFD analysis tools
- Apply these tools to the development of hardware technology and concepts
- Define judicious, relevant cold flow experiments to provide tool validation, technology and concept verification, and to further expand fluid dynamics knowledge and understanding
- Apply the technical knowledge, design and analysis tools, experimental data, and hardware concepts to support the development and anomaly investigation of flight hardware







Scope



For the purposes of the TD64, turbomachinery fluid dynamics includes the following hardware elements

- **Turbine primary flowpath**
  - Blading (vanes, blades, struts, guide vanes)
  - Manifolds (toruses, volutes)
  - Pipes and ducts (including diffusers)
- **Pump primary flowpath**
  - Blading (inducer, impeller, diffuser vanes)
  - Manifolds (toruses, volutes)
  - Pipes and ducts (including crossovers)
- **Turbomachinery cavities**
- **Elements with a prescribed motion**
  - Valves
  - Bearings

Another Roadmap - Sigh
My Reasons for Disliking Them



- **MSFC is an applications center with no research and technology programs**
  - With the demise of the ETO program in the mid-1990s, all technology paid for through projects
  - Projects come and go with an ever-increasing frequency, rarely providing long-term, continuous funding for technology
  - Projects interested in funding their problem of the moment
- **Although in the Turbomachinery Fluids Team we try to dedicate some of our time to technology development that has general applicability, our project work load has us stretched very thin**
  - Dates on our technology roadmaps have little meaning because
    - We work the technology when we have time
    - The technology has suddenly become urgent to a project, and the well-thought out plan goes out the window

Technology tasks are generally funding because of some urgency, not because some well-thought out, well-blessed plan says its time to work them

Good Reasons for the Roadmap Process



- **Within the Turbomachinery Fluids Team**
  - Forces us to step back and define the whole problem
    - What is turbomachinery fluid design and analysis and what should it be?
  - Provides us with a view of our current level of proficiency and where we need to be in order to work areas in the whole problem
  - Identifies the areas where we are deficient
  - Defines the process by which to improve our proficiency
  - Helps us to identify items of improvement that are necessary for multiple areas of the whole problem
- **For Team Leader/Group Leader**
  - Identifies items that will achieve the most bang for the buck when we get funding, piecemeal or otherwise, for technology improvements
  - Provides a good visual aid for project managers to show what areas have to be worked for their projects and how it fits into the overall plan

The Roadmap Works for the Turbomachinery Fluids Team in the Context of a Highly Flexible Plan that Helps Us Define Our Current Capabilities, Our Required Capabilities, and the Process to Get from One to the Other

MSFC Turbomachinery Fluids Roadmap Development



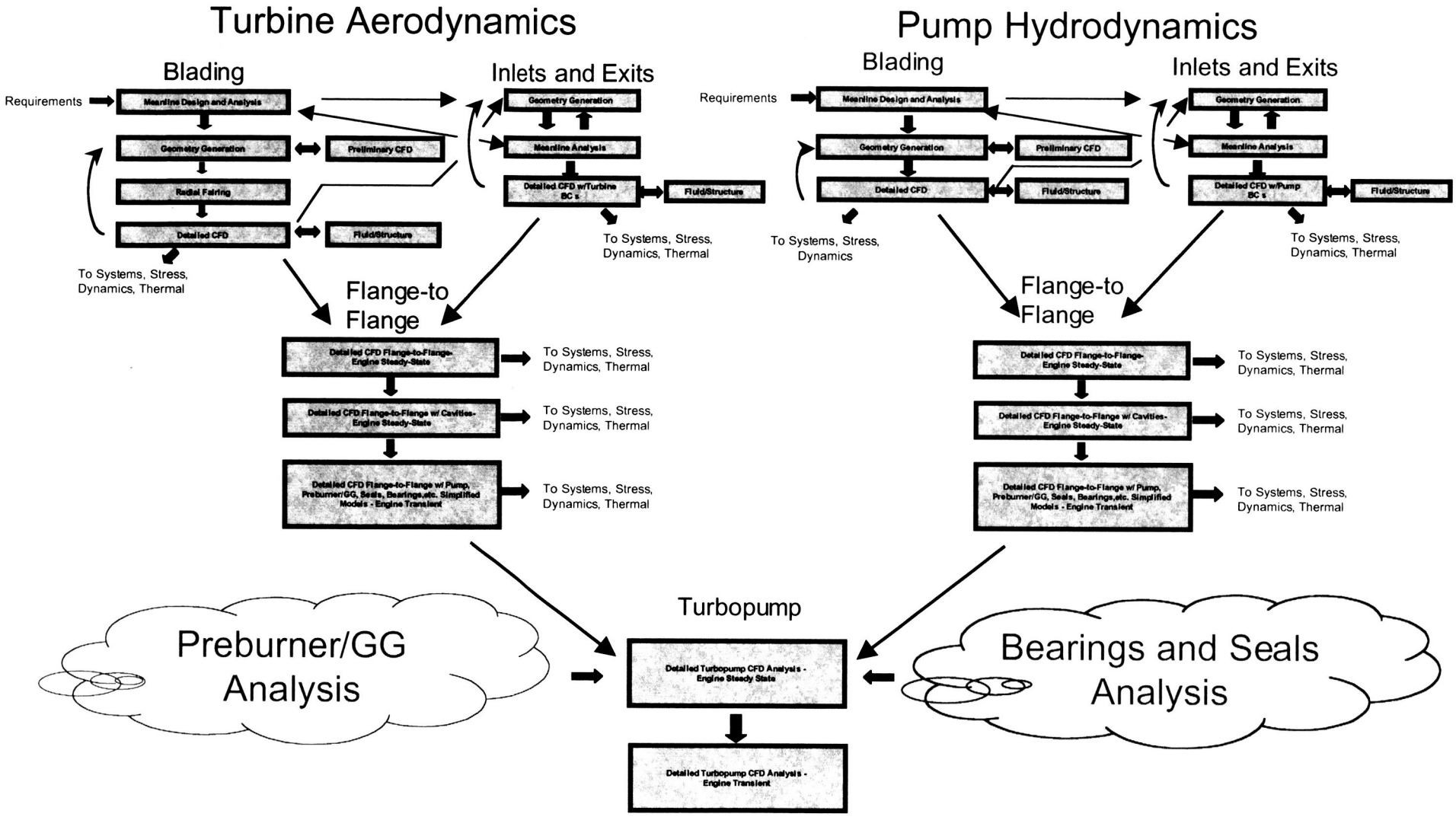
- **Roadmap development is a work in progress**
  - Map itself not completed
  - Input needed to develop the map contained in this presentation
- **The roadmap represents our capabilities in TD64**
- **As a work in progress, the roadmap has deficiencies and omissions**
  - Bearings, valves, seals currently not considered
- **Roadmap will provide industry and academia insight into MSFC s plans for turbomachinery fluid dynamics**
- **We are soliciting feed-back from the turbomachinery and fluid dynamics community**
  - Identify deficiencies and omissions in the roadmap
  - Identify areas of where improvements are needed by the entire community
  - Identify areas where TD64 seems to laf the turbomachinery community
  - Identify ways to improve proficiency levels, TD64 and industry-wide

MSFC Turbomachinery Fluids Roadmap Development

- **Our roadmap considers the next 5 years**
- **Before we begin a roadmap, a few items had to be considered**
  - Define the whole turbomachinery fluid dynamics problem
  - What will our project requirements be in the next 5 years based on what we know today?
  - Are there general problems that we can t tackle in 5 years, but need to start the ground work for now to meet space transportation goals?
  - What are our current capabilities in fluid design and analysis as applied to areas of the whole problem?

This Presentation Discusses the Items that Must be Defined to Develop the Roadmap

Turbopump Fluid Design and Analysis - The Whole Problem



Project Requirements

- **Particular concepts to meet project goals present challenges for turbomachinery**
  - Full-flow staged combustion cycle engines are experiencing weight, turbine blade stress, and turbine performance issues
    - Require turbine manifold and blading (axial, subsonic) design and analysis
  - Turbine-based combined cycle rocket and upper-stage engine turbomachinery require deep-throttle capability
    - Require turbine manifold design and analysis capability and hardware concept development
    - Require pump diffuser design and analysis capability and hardware concept development
    - Compact radial turbine concepts should be investigated
- **All turbomachinery concepts will have to deal with high and low cycle fatigue to address reliability goals**
  - Unsteady CFD analysis for turbines and pumps required
  - Efficient methods of providing unsteady fluids loads to structural models needed
  - CFD analysis of turbomachinery during start and shutdown transients necessary

Project Requirements



- **Inducer cavitation must be addressed for pump performance and reliability goals**
  - Cavitation modeling/prediction required
  - Concepts to reduce inducer cavitation needed
- **Hydraulic turbines used low pressure turbomachinery**
  - Design and analysis capability needed

Current and Required Capabilities



- **The whole problem was broken into categories**
  - Turbine blading design and analysis
  - Pump blading design and analysis
  - Inlet and exit design and analysis
  - Flange-to-flange analysis
  - Turbopump analysis
- **Readiness levels were developed**
  - Design and analysis capability
  - Validation data availability
  - Turn around time required
- **Current capabilities were assigned a readiness level along with issues needing to be worked**
- **5 year required capabilities were assigned based on discipline and project needs**

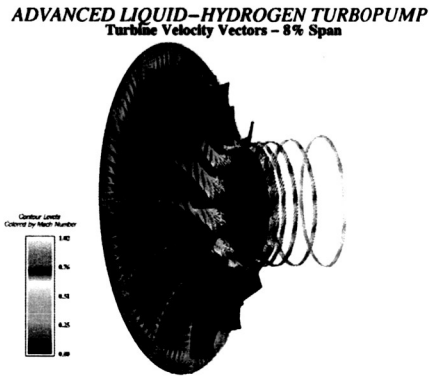
Design and Analysis Readiness Levels

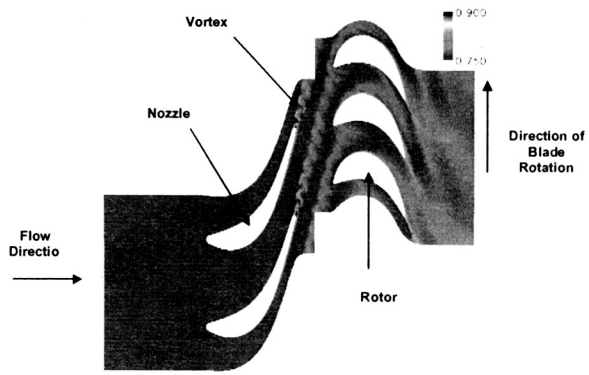
Level	Design and Analysis	Validations Data	Turn Around Time
0	Not attempted with current tools	No data in house; little data in literature	Requires more than 6 months
1	Have conducted preliminary work	Experimental result shown in literature but little geometric or BC detail to enable problem simulation	Requires more than 3 months but less than 6 months
2	Have applied to a simplified problem	Steady or time-averaged overall or 'flange-to-flange' pressures and temperatures available; flows and torque available for pumps	Requires more than 1 month but less than 3 months
3	Have applied to a relevant problem, issues to be worked	Steady or time-averaged overall pressures and temperatures and detailed flow path and/or row information; Flow vis. may be available; Fluctuating pressures on walls may be available	Requires more than 1 week but less than 1 month
4	Routinely apply to relevant problems, issues to be worked	Time-averaged temperatures and unsteady and time-averaged pressures in flow path and on blading	Requires more than 1 day but less than 1 week
5	Routinely applied to relevant problems, currently no issues to be worked	Multiple datasets with time-averaged tempertures and unsteady and time-averaged pressures; details like boundary measurements and all velocity components resolved	Requires 1 day or less

Turbine Blading



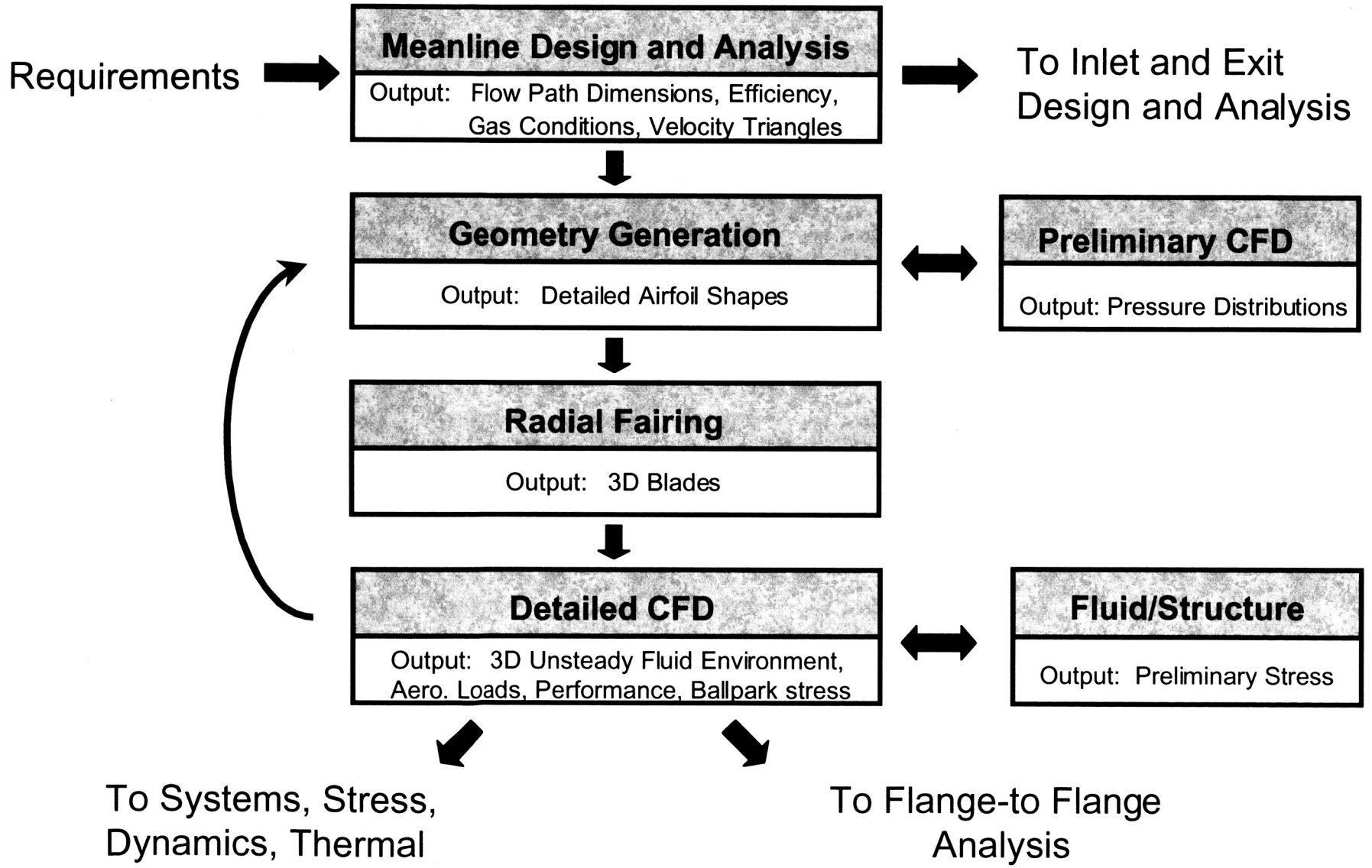
- **Turbine blading categories divided by turbine type; these categories represent types we have used for rocket engines in the past or considering in the future**
  - Axial
  - Radial/mix flow
  - Hydraulic
  - Counterrotating
- **Required readiness levels are set for a 5 year time frame**
- **Required readiness levels chosen based on current and projected project needs**





SSME LPOTP Turbine

Turbine Blading Aerodynamic Design and Analysis



Turbine Stage Design & Analysis Tools Used at MSFC

- **Meanline Tools**
  - MLFPDesign - Meanline design
  - MLOD - Meanline analysis
- **Geometry Generation**
  - Airfoil
- **Radial Fairing**
  - Fairing
- **CFD Grid Generation**
  - Wildgrd - 2D grid generator for Wildcat
  - Corgrd - 3D grid generator for Corsair
- **CFD Analysis**
  - Wildcat - 2D unsteady compressible CFD
  - Corsair - 3D unsteady compressible CFD
- **CFD Post-Processing**
  - Postflt - Corsair post-processor
  - Fieldview - general fluid post-processor

Moving to Aarvark and Phantom

Turbine Blading Readiness Matrix

Element	Design and Analysis			Validation Data			Turn Around Time		
	Current Readiness Level	Required Readiness Level	Issues	Current Readiness Level	Required Readiness Level	Notes	Current Readiness Level	Required Readiness Level	Issues
Blading									
Axial									
Subsonic	4	4	K,L	4	4	SSME , ATD (time-averaged only), TAFT, LSRR	2	3	A,B,C,D,E
Transonic	4	4	K,L	4	4	E^3, GGOT (Time-averaged), VBI(unsteady, phase-resolved)	2	3	A,B,C,D,E
Supersonic	3	4	F,G,K,L	4	4	TPO, Fastrac (Engine), Simplex (Turbopump)	2	3	A,B,C,D,E
Partial Admission	3	4	G,K,L	1	4	Various reports, Simplex (Turbopump)	1	2	A,B,C,D,E
Radial/Mixed Flow	2	3	G,H,I,K,L,M	1+	2	Compact Radial Turbine (P&W/GRC)	1	2	A,B,C,D,E
Hydraulic	2+	4	G,H,J,K,L	1	2	LPOTP (Engine)	2	3	A,B,C,D,E
Counterrotating	3	3	G,K,L	1	1	AETB Report	2	2	A,B,C,D,E

Assume 1 -2 Stages, Periodic Solutions (except for Partial Admission), and 32 CPUs available for periodic solutions (96 CPUs for partial admission)

Issues Key

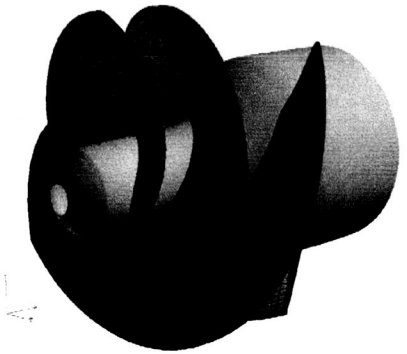


	Issue		Issue
A	Upgrade algorithms for speed needed	I	Geometry generation code development work required
B	Generalization of domain decomposition for memory and parallel processing efficiency needed	J	General fluid properties implementation/validation required
C	Automation/Template Development of grid generation tools for turbomachinery needed	K	Methodology to pass fluids loads/frequencies to structural models required
D	Generalization/automation of Turbomachinery CFD pre- and post-processing tools needed	L	Improvements to turbulence models for off-design conditions needed
E	Design and analysis tool integration required	M	Radial blade geometry generator needed
F	Meanline loss model improvement required	N	Hydrodynamamic design system selection/development needed
G	Further code validation needed	O	Two-phase flow modeling needed
H	Meanline module development and implementation required		

Note: This key is used throughout the presentation

Pump Blading

- **Pump hydrodynamic design and analysis capabilities lag the turbine aerodynamic design and analysis capabilities in TD64**
- **Pump blading categories divided by element**
  - Inducer
  - Impeller
  - Vaned Diffusers
- **Final blading category includes the coupled inducer /impeller /diffuser**

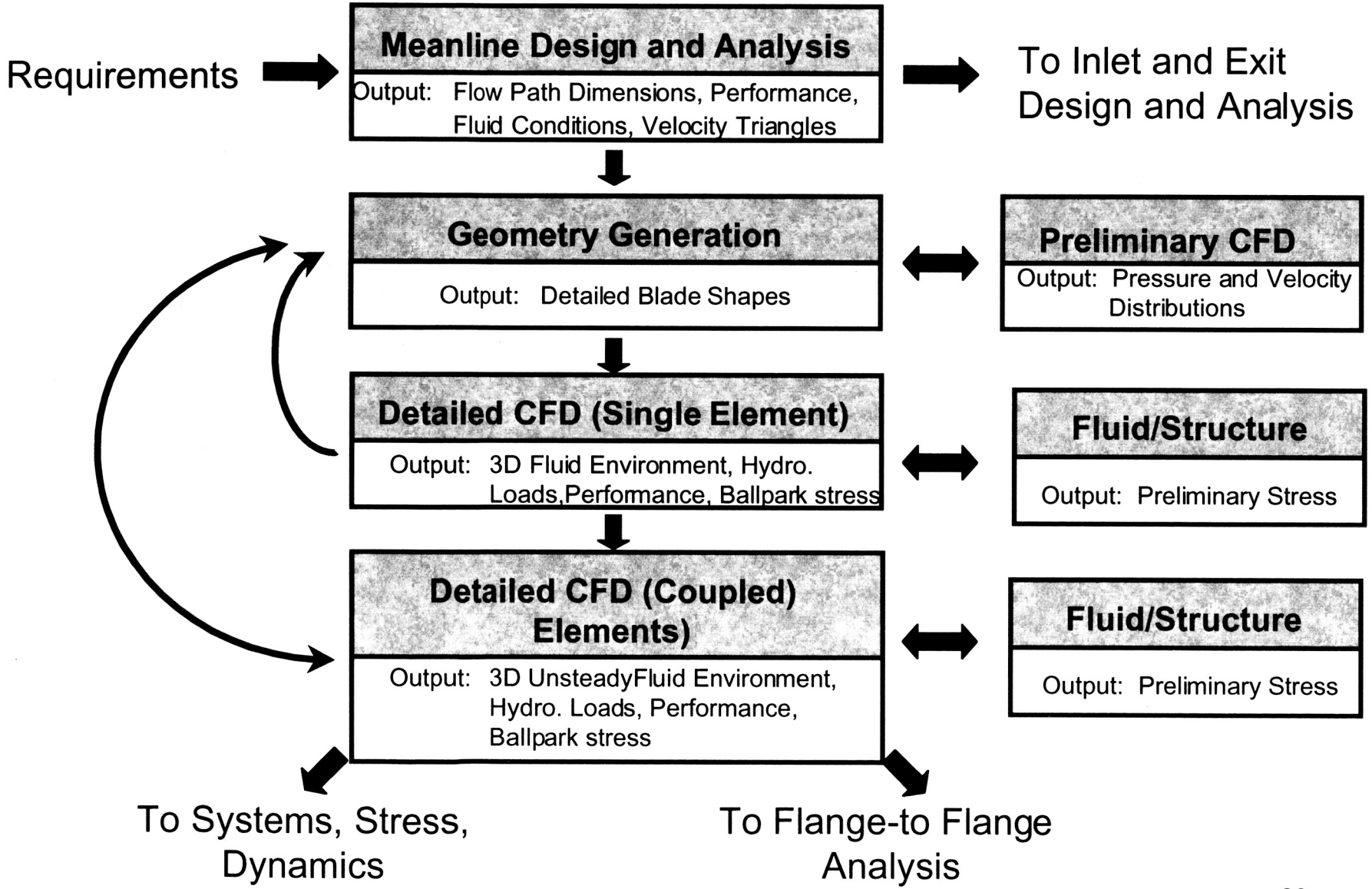


Inducer Grid



Unshrouded Impeller Technology

Pump Blading Hydrodynamics Design and Analysis



Pump Stage Design & Analysis Tools Used at MSFC



- **Meanline Tools**
  - Under evaluation - Meanline design
  - Under evaluation - Meanline analysis
- **Geometry Generation**
  - Under evaluation
- **CFD Grid Generation**
  - Corgrd - 3D grid generator for Corsair
- **CFD Analysis**
  - Corsair - 3D unsteady compressible CFD
- **CFD Post-Processing**
  - Postflt - Corsair post-processor
  - Fieldview - general fluid post-processor

} Moving to Phantom

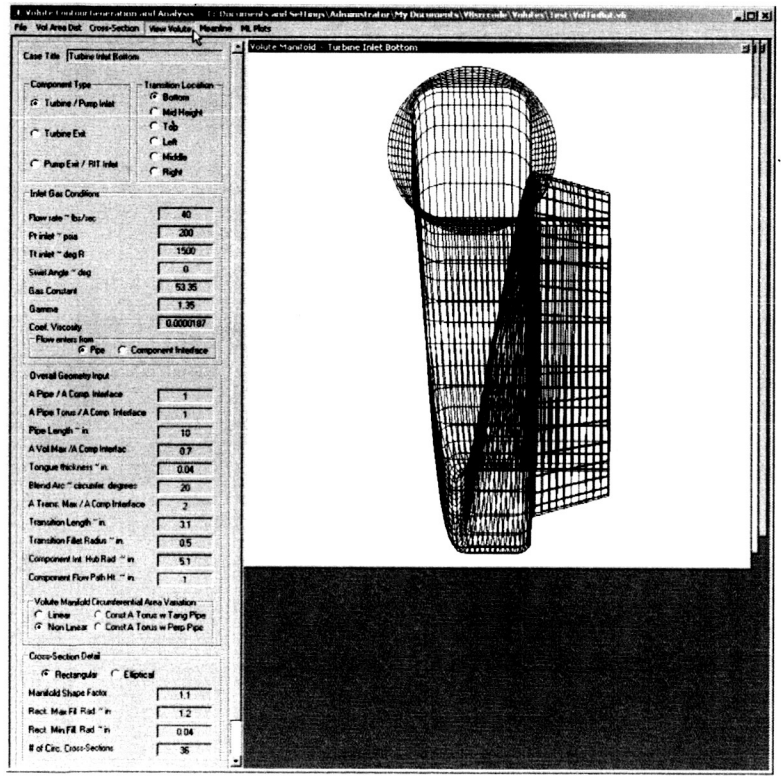
Pump Blading Readiness Matrix

Element	Design and Analysis			Validation Data			Turn Around Time		
	Current Readiness Level	Required Readiness Level	Issues	Current Readiness Level	Required Readiness Level	Notes	Current Readiness Level	Required Readiness Level	Issues
Blading									
Inducers	2	4	G,I,J,K,L,M,N	3	4	To be Added	2	4	A,B,C,D,E
Impellers	3	4	G,I,J,K,L,M,O	3	4	To be Added	2	4	A,B,C,D,E
Vaned Diffusers	3	4	G,I,J,K,L,M,O	2	4	To be Added	3	4	A,B,C,D,E
Coupled Elements (inducer + Impeller + Diffuser)	1	4	G,I,J,K,L,M,N, O	2	3	To be Added	0	2	A,B,C,D,E

Assume 1 Stage Impeller, Full Annulus, and 32 CPUs available for non-coupled Elements, 96 CPUs for coupled elements solution

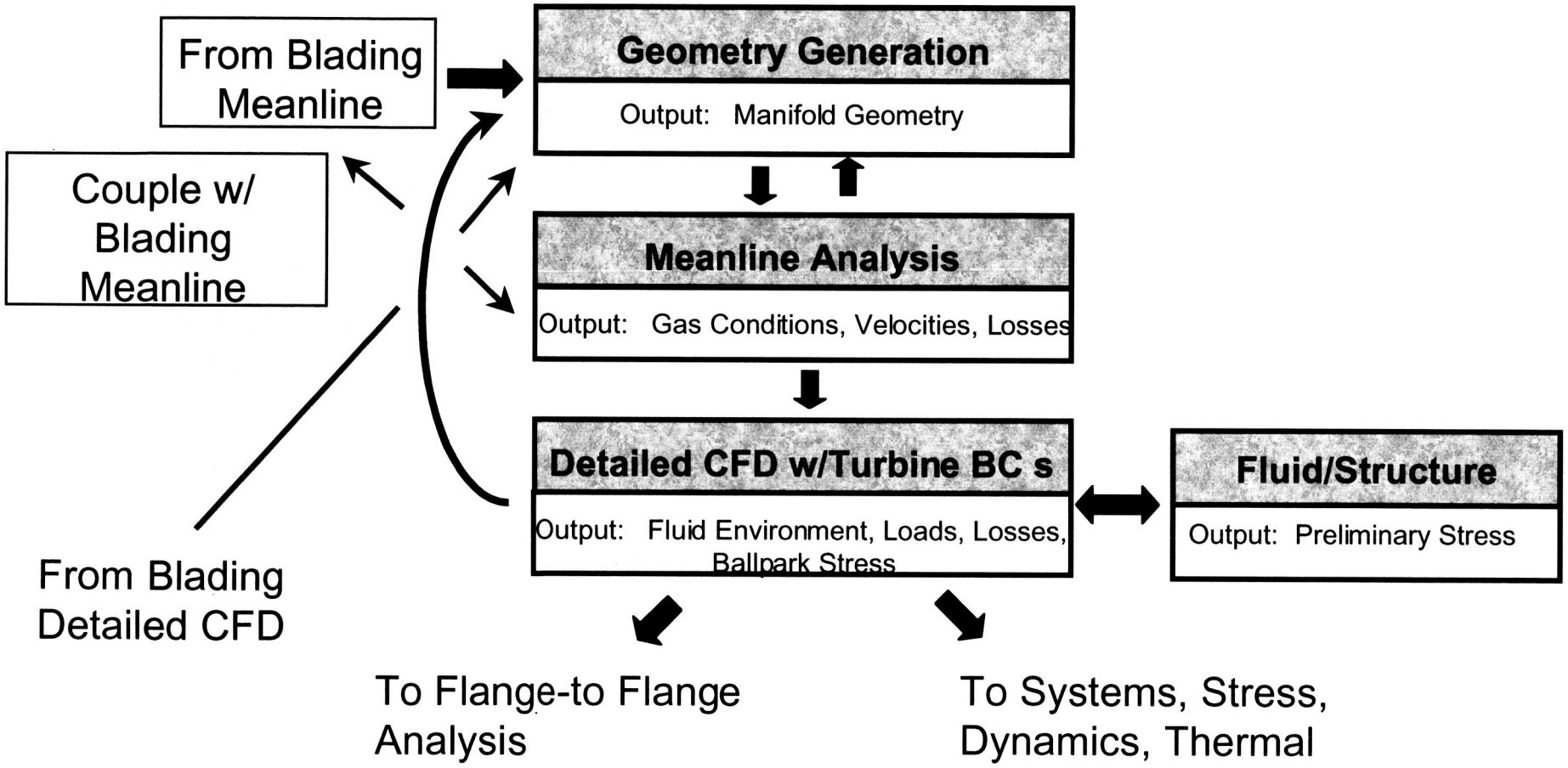
Inlets and Exits

- Pipe and duct analyses are routinely conducted
- Manifold design and analysis capabilities lag the blading design and analysis capabilities in TD64



Volute Flow Path Design - VolGen

Manifold Aerodynamic/Hydrodynamic Design and Analysis



Pump Stage Design & Analysis Tools Used at MSFC

- **Meanline Tools**
  - VolGen - Meanline design and analysis
- **Geometry Generation**
  - VolGen
- **CFD Grid Generation**
  - Gridgen
- **CFD Analysis**
  - Corsair - 3D unsteady compressible CFD
- **CFD Post-Processing**
  - Postflt - Corsair post-processor
  - Fieldview - general fluid post-processor

} Moving to Phantom

Inlet and Exits Readiness Matrix

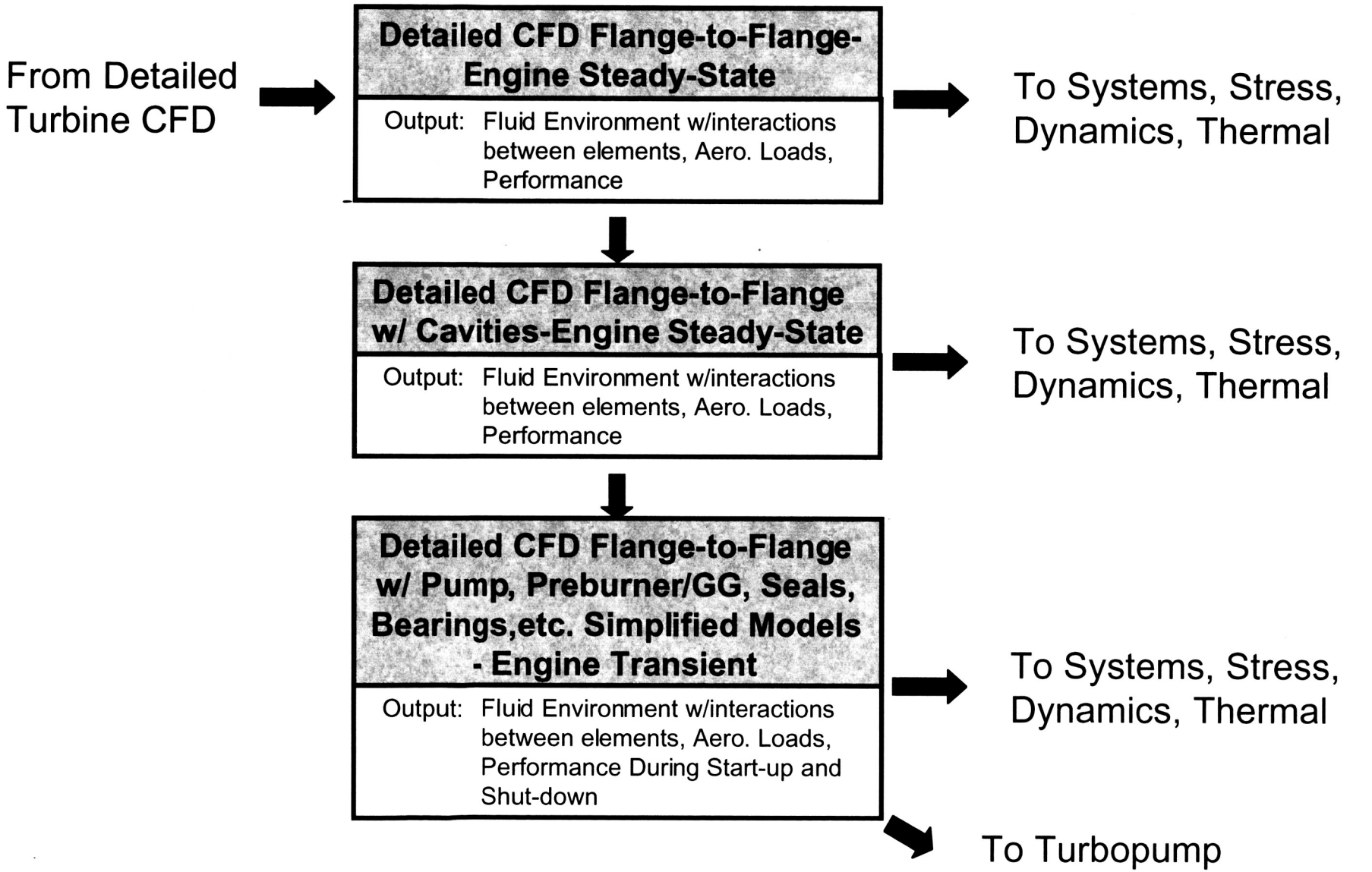
Element	Design and Analysis			Validation Data			Turn Around Time		
	Current Readiness Level	Required Readiness Level	Issues	Current Readiness Level	Required Readiness Level	Notes	Current Readiness Level	Required Readiness Level	Issues
Inlet/Exits									
Pipe and Ducts	**4**	**4**	-	**4**	**4**	To be Added	**4**	**5**	A,B,C,D,E
Manifolds	**2**	**4**	G,H,I,J,K,L,O	**3**	**4**	GGOT, others to be added	**1**	**2**	A,B,C,D,E

Assumes there may be struts or vanes in the inlet and exits

Flange-to-Flange Analysis

- **Flange-to-flange analysis currently not conducted at MSFC**
  - Necessary to achieve correct boundary conditions and interactions
- **Begin to integrate multiple domain analysis (turbine/pump + cavities)**
- **Flange-to-flange analysis includes**
  - Primary flowpath only at Engine Steady State conditions
  - Primary flowpath + Cavities at Engine Steady State conditions
  - Primary flowpath + Cavities at Engine Transient conditions w/ simplified models for preburner/GG, seals, bearings, and turbine or pump
- **Engine transient analysis is needed ASAP; however, we will not be ready for such an analysis within 5 years**
  - Readiness levels will still be low in 5 years, but ground work will be laid for the transient analysis

Flange-to-Flange Aerodynamic/Hydrodynamic Analysis



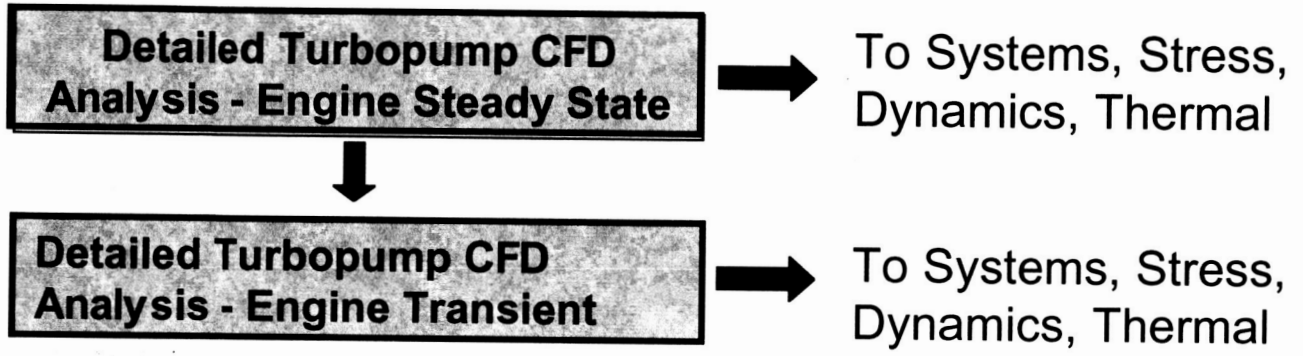
Flange-to-Flange Readiness Matrix

Element	Design and Analysis			Validation Data			Turn Around Time		
	Current Readiness Level	Required Readiness Level	Issues	Current Readiness Level	Required Readiness Level	Notes	Current Readiness Level	Required Readiness Level	Issues
Flange-to-Flange									
Primary Flow Path, Engine Steady State	**0**	**3**	G,H,I,J,K,L,M, N,P,Q	**2**	**2**	Engine Data	**0**	**1**	A,B,C,D,E
Primary Flow Path + Cavities, Engine Steady State	**0**	**3**	G,H,I,J,K,L,M, N,P,Q	**2**	**2**	Engine Data	**0**	**1**	A,B,C,D,E
Primary Flow Path + Cavities, Engine Transient	**0**	**1**	G,H,I,J,K,L,M, N,P,Q	**2**	**2**	Engine Data	**0**	**1**	A,B,C,D,E

Turbopump Fluid Dynamics Analysis

- **For a turbopump analysis, further integration of multiple domain analysis is necessary (preburner/gg + turbine + pump + cavities + bearings + seals)**
- **Multidisciplinary Analysis should be incorporated at some point to include rotordynamics, stress, and thermal analysis in addition to fluids**
- **Turbopump analysis includes**
  - Engine steady state conditions
  - Engine transient conditions
- **Because so many steps must be completed before we are ready for a turbopump analysis, readiness levels will remain low in 5 years**

Turbopump Fluid Dynamics Analysis



Turbopump Readiness Matrix

Element	Design and Analysis			Validation Data			Turn Around Time		
	Current Readiness Level	Required Readiness Level	Issues	Current Readiness Level	Required Readiness Level	Notes	Current Readiness Level	Required Readiness Level	Issues
Turbopump									
Engine Steady State	**0**	**1**	G,H,I,J,K,L,M, N,P,Q,R	**2**	**2**	Engine Data	**0**	**0**	A,B,C,D,E
Engine Transient	**0**	**1**	G,H,I,J,K,L,M, N,P,Q,R	**2**	**2**	Engine Data	**0**	**0**	A,B,C,D,E

Current Work to Address Items on the Roadmap

- **Manifold flow path design and analysis**
  - Initial meanline and geometry generation tools developed - Frank Huber
- **Unsteady, generalized fluids CFD codes are being developed - Dan Dorney (TD64) and Doug Sondak (Boston University)**
  - Aarvark (2D) and Phantom (3D) will be used to analyze gas and hydraulic turbines and pumps
- **Cavitation modeling is being developed and validated - (Ashvin Hosangadi CRAFT Tech.)**
  - Models will be implemented into Aardvark and Phantom
- **Wide flow diffuser concepts will be developed using Phantom and the Rocketdyne code, Enigma - TD64 and Rocketdyne**