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Dose Calculations for Nuclear Thermal Rocket Exhaust

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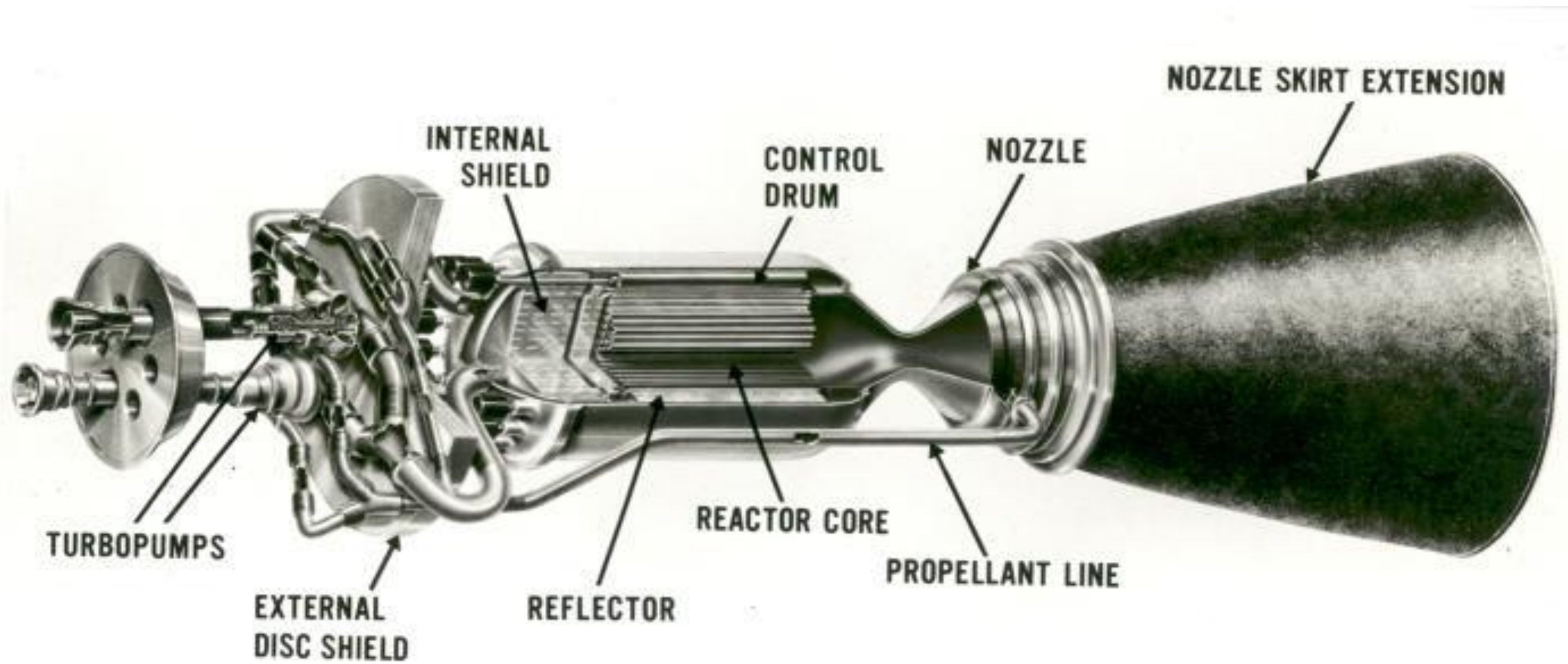
Outline

- NTR History
- Model Development
- Model Input/Source Term
- Results

Introduction

- NTR development was very mature by 1970
- Static rocket firings were performed for up to an hour in the Nevada Test Site.
- The firing intensity and durations were very prototypic of in-space firings needed for trajectories to the Moon, Mars or beyond
- Measurements of upward-directed exhaust showed some fission-product release in the plume
- Most of these fission products would be very short-lived
- Given that the rocket firings would be in space, would these releases be negligible in terms of health and environmental impacts to earth?

NTR Design



Courtesy DOE, NASA

NERVA

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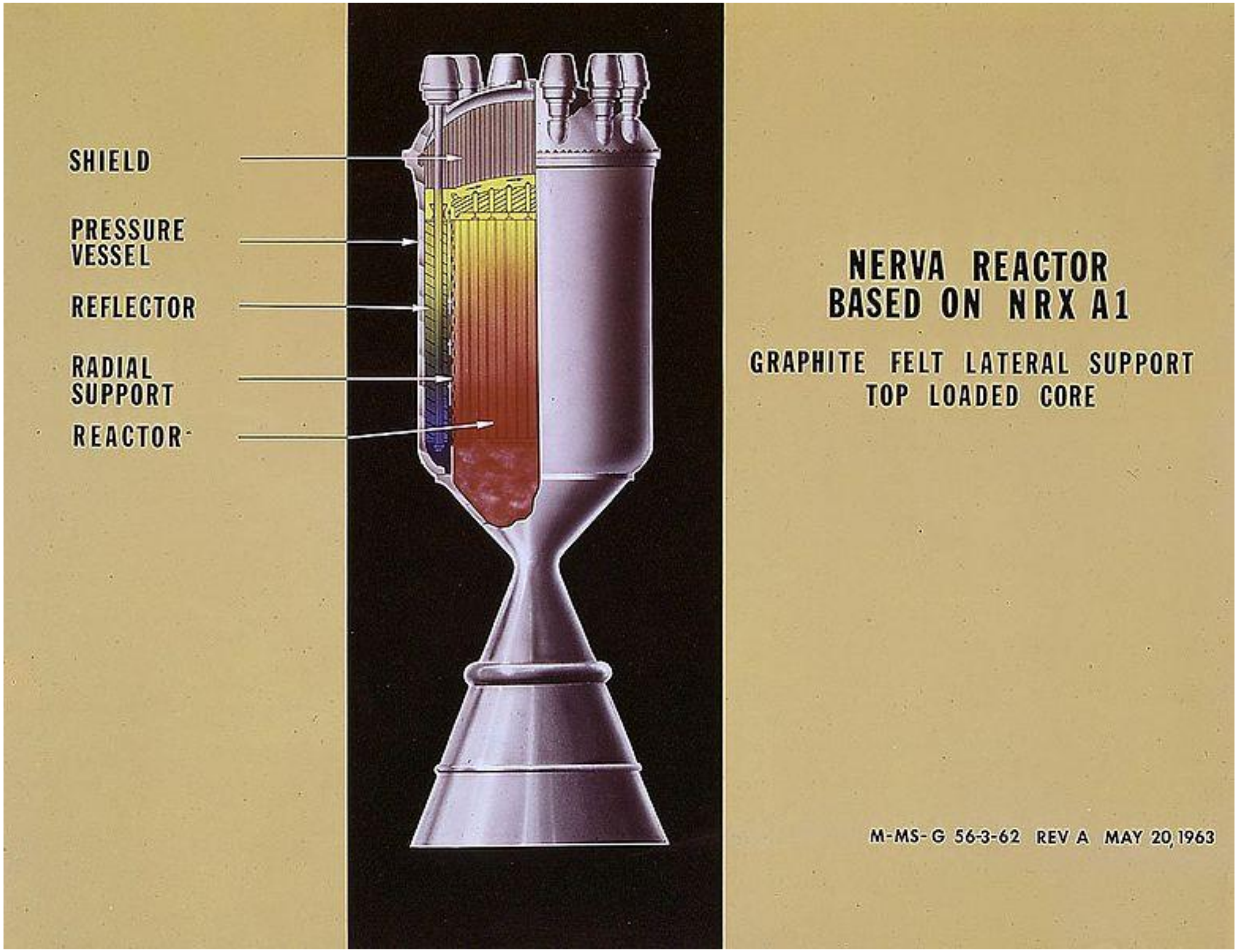
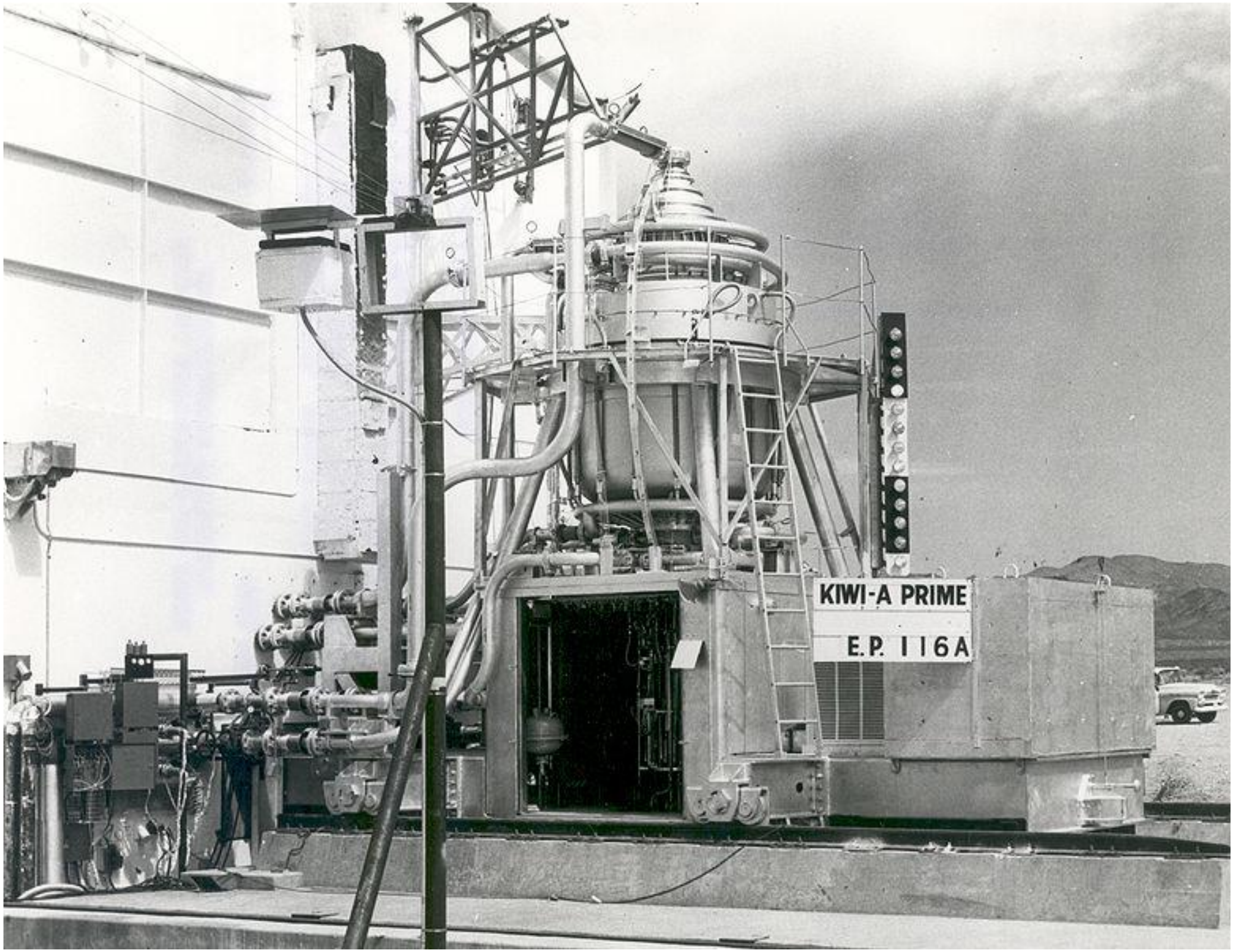


Courtesy DOE, NASA

KIWI-A Prime

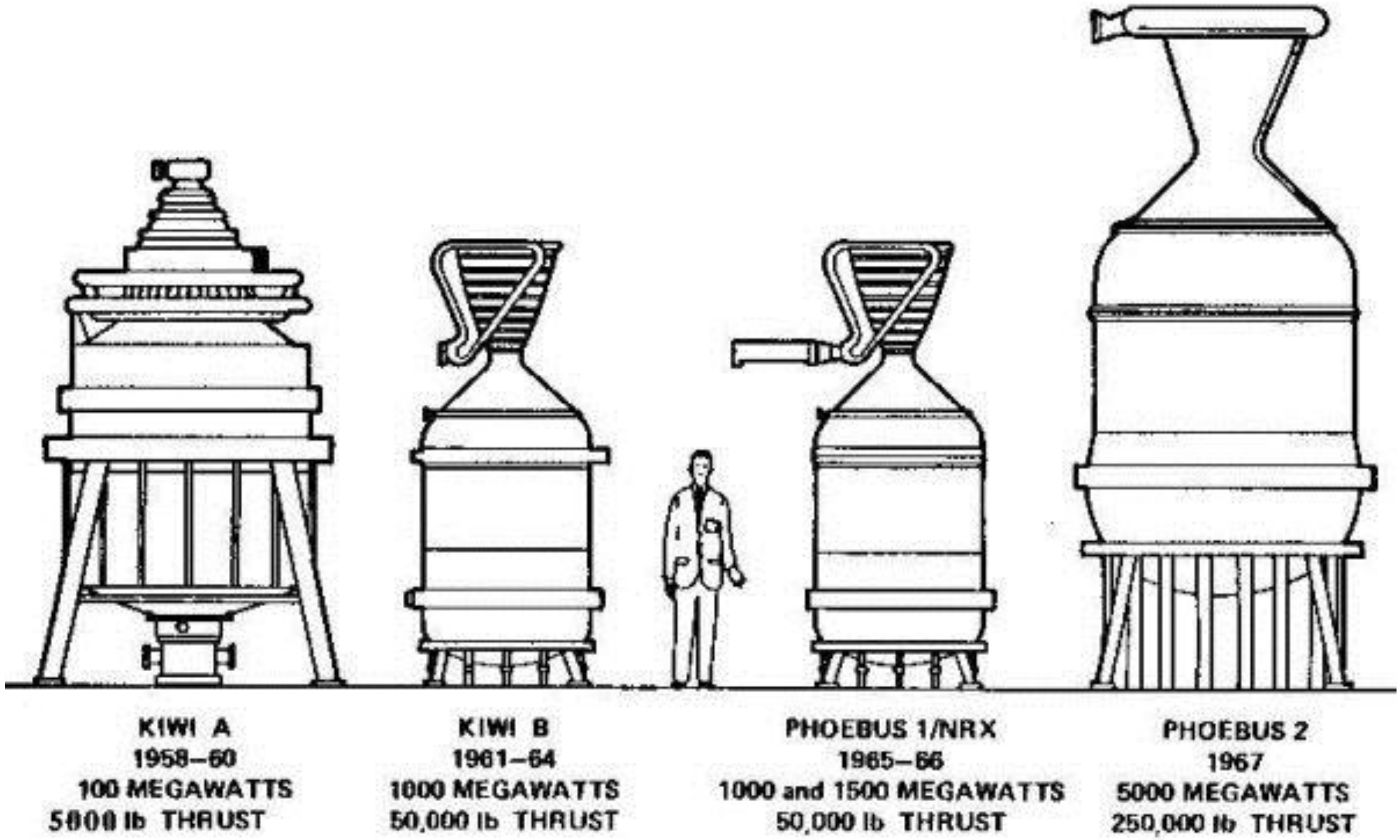


Courtesy DOE, NASA

KIWI Test

Courtesy DOE, NASA

KIWI and PHOEBUS Comparison



Courtesy DOE, NASA

NTR Experiment Results

Sample of high-power, long-duration firings

Name	Experiment Plan Number	Nozzle Chamber Temp (K)	Power (MW)	Approx. Full-Power Duration (s)
Phoebus 1A	4	2683	1070	690
NRX-A5	3	2477	980	1224
NRX-A5	4	2533	1030	971
Phoebus 1B	4	2755	1340	1940
NRX-A6	3A	2560	1140	3947
Phoebus 2A	4	2510	4010	1122
PEWEE 1	3	2810	503	3042

Estimated Releases from NTR Tests

TABLE 2. Measured release fractions from NTR ground tests (Friesen 1995).

Isotope	Cumul. Yield	Ph-1A, P4	NRX-A5, P3	NRX-A5, P4	Ph-1B, P4	NRX-A6, P3A	Ph-2A, P4	P-1, P3
Sr-91	0.0572	3.78E-03	1.29E-04		1.91E-02	1.33E-03	1.98E-03	4.97E-03
Sr-92	0.0584	3.78E-03	9.75E-04			9.51E-04	6.34E-04	6.66E-03
Zr-95	0.0635	4.02E-04						
Mo-99	0.058	4.72E-05		3.50E-02	9.14E-03	0.00E+00	2.33E-04	2.38E-03
I-131	0.03365	6.67E-04	5.58E-04	5.64E-02	5.56E-02	6.43E-03	6.90E-03	2.59E-02
Te-132	0.0464	9.94E-04	6.65E-04	7.77E-02	5.58E-02	8.75E-03	6.22E-03	3.52E-02
I-133	0.0661	8.63E-04	3.06E-04	5.22E-02	4.39E-02	5.16E-03	5.59E-03	
Te-134	0.0656	3.00E-04					7.40E-04	4.79E-03
I-134	0.0763	5.06E-02	5.59E-05		1.44E-02	2.51E-03	5.50E-04	5.18E-03
I-135	0.0601	8.77E-04	1.86E-04	2.98E-02	9.36E-03	1.38E-03	1.50E-03	
Ba-139	0.0633	6.33E-04	9.26E-05		6.69E-03	8.03E-04	1.37E-03	2.95E-04
Average		5.72E-03	3.71E-04	5.02E-02	2.68E-02	3.04E-03	2.57E-03	1.07E-02

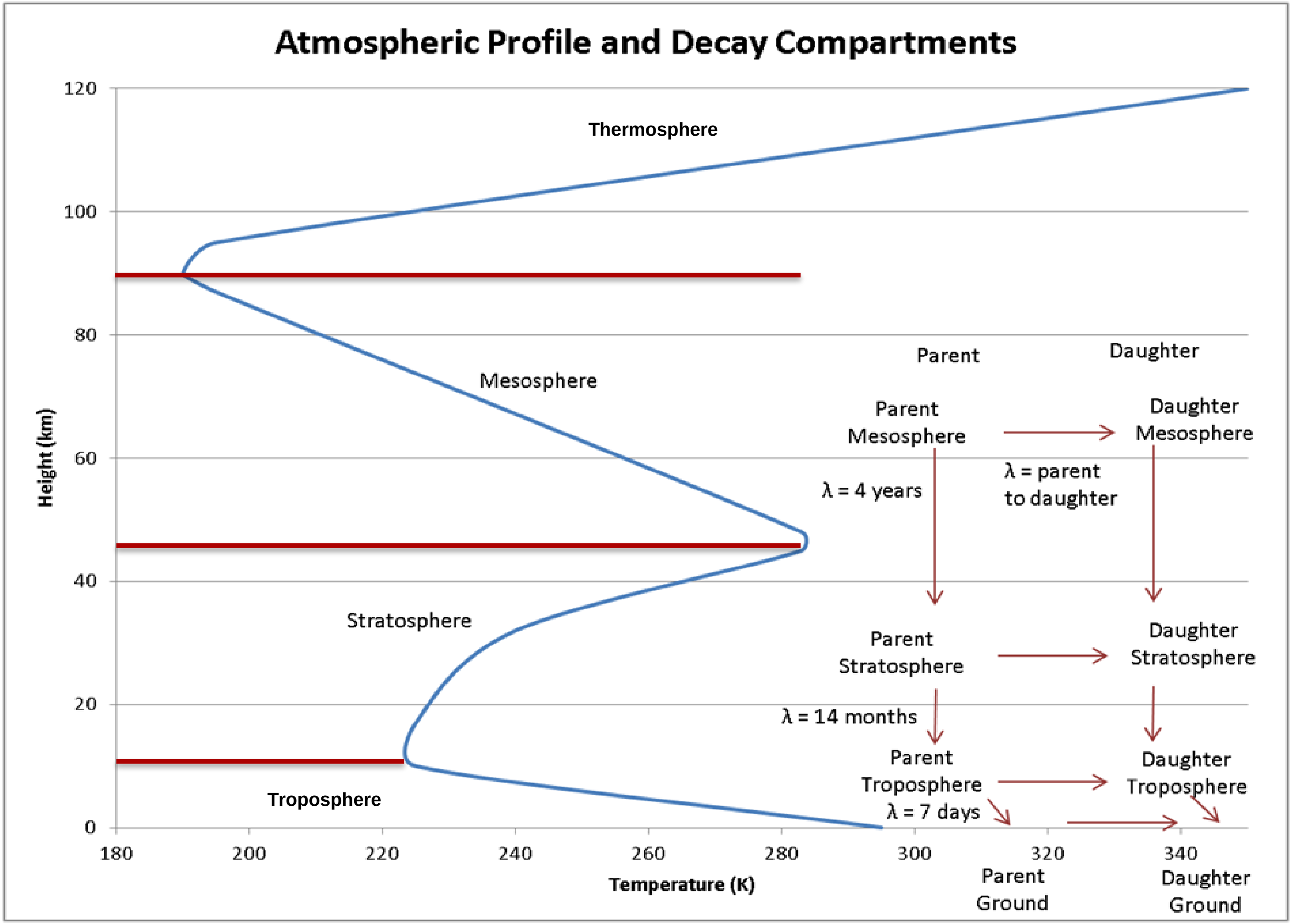
The total fission product inventory upon which the release fraction is based is determined by the calculated energy produced by the test and the cumulative fission yield for that isotope for fast fission.

Model Development

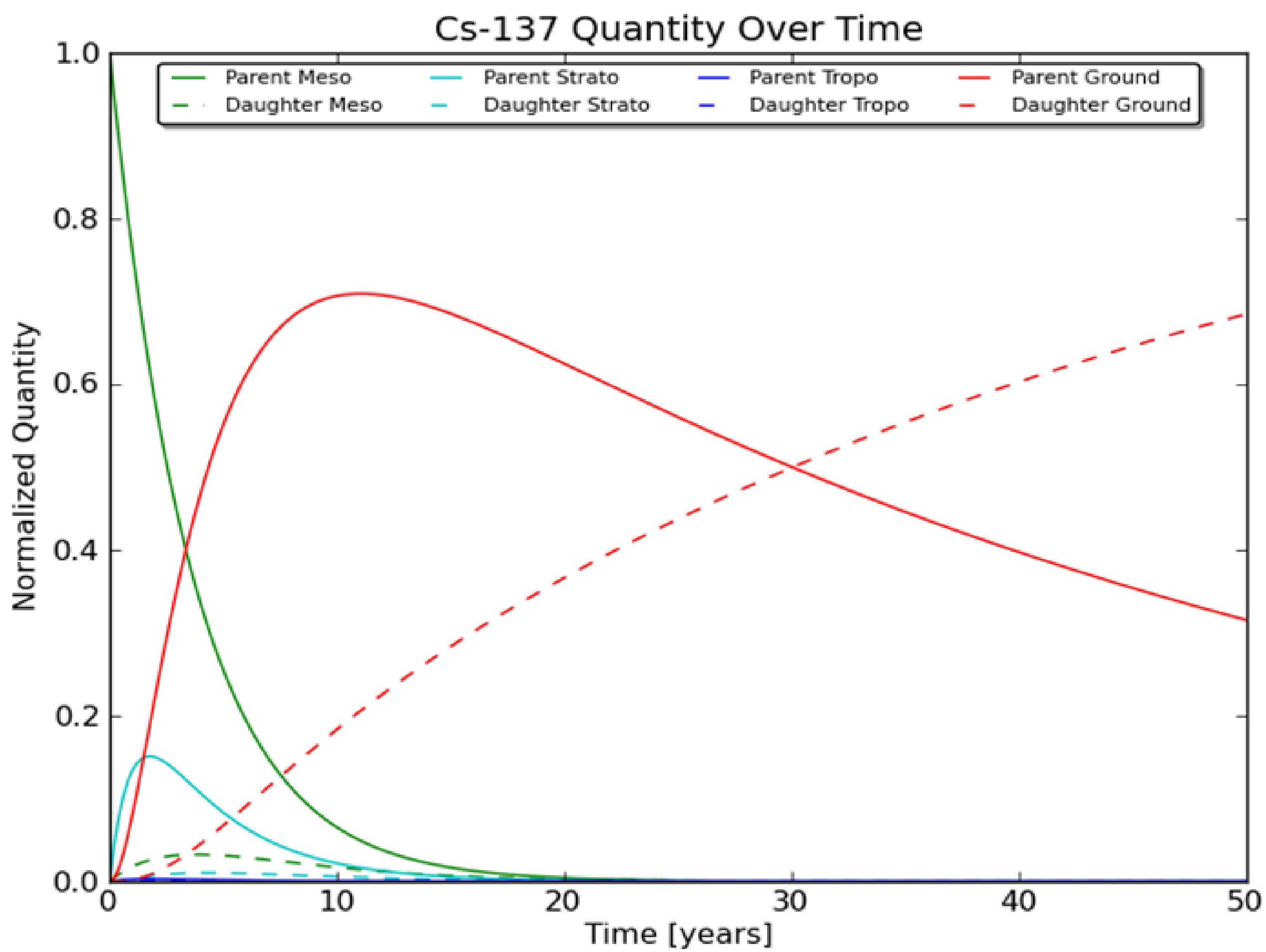
Model Overview

- Exhaust assumed to be released at 100 km altitude and distributed uniformly over the globe at that altitude
  - Expected firings would be at 400 km altitude or higher, with some subsequent loss of fission products to space
- Exponential decay factors between compartments obtained from previous atmospheric weapons tests
- 4 atmospheric compartments
  - Mesosphere (45-85 km), $\lambda = t_{1/e}$ = 4 years
  - Stratosphere (10-45 km), $\lambda = t_{1/e}$ = 14 months
  - Troposphere (0-10 km), $\lambda = t_{1/e}$ = 7 days
  - Ground
- Took into account daughter product build-up and decay
- Radionuclides used in the analysis were scaled to Phoebus-1B test plan report

Model Compartments



Example Radionuclide Output



This shows how Cs-137 transfers from the mesosphere down to the ground, as well as to the ground state of its daughter isotope, Ba-137, after a brief isomeric transition from a Ba-137 excited state (2.55-minute half-life, not explicitly shown).

Dose Model

- Dose was calculated from exposure via:
  - Inhalation
  - Cloudshine
  - Groundshine
  - Ingestion (for dominant isotopes)
  - Resuspension
- Removal due to weathering (absorption into the ground) was not included
- Dose conversion factors were taken from ICRP-72
- "Total Dose" is the total dose per person integrated over 50 years

Selected Results

Isotope	Release (Ci)	Inhalation Dose (Sv)	Cloudshine Dose (Sv)	Groundshine Dose (Sv)	Total 50-yr Individual Dose (Sv)	Frac. of 1-yr Bkg. Dose
Sr-89	291	2.14E-15	3.52E-18	5.77E-14	5.98E-14	2.49E-11
Sr-90	**2**	**4.34E-14**	**5.77E-18**	**1.04E-11**	**1.04E-11**	**4.35E-09**
Sr-91	48000	2.86E-14	7.83E-18	1.09E-13	1.38E-13	5.74E-11
Zr-95	**468**	**3.96E-14**	**1.75E-15**	**5.43E-12**	**5.47E-12**	**2.28E-09**
Mo-99	3400	3.59E-17	1.71E-18	2.31E-16	2.69E-16	1.12E-13
Te-129	79000	2.58E-20	7.73E-23	1.24E-18	1.26E-18	5.27E-16
I-131	4100	4.56E-15	4.19E-17	1.73E-14	2.19E-14	9.12E-12
I-133	59000	3.78E-17	5.88E-18	1.13E-15	1.17E-15	4.89E-13
Te-134	2220000	1.03E-20	8.26E-20	1.52E-19	2.44E-19	1.02E-16
I-134	530000	9.21E-22	9.44E-21	1.47E-20	2.51E-20	1.04E-17
I-135	36000	1.82E-19	2.61E-19	3.85E-18	4.29E-18	1.79E-15
Cs-136	4	2.38E-18	7.31E-19	4.05E-16	4.08E-16	1.70E-13
Cs-137	**3**	**1.22E-14**	**9.19E-19**	**4.33E-13**	**4.45E-13**	**1.86E-10**
Ba-139	130000	6.55E-22	1.87E-22	1.27E-21	2.11E-21	8.80E-19
Ce-144	**85**	**4.08E-14**	**2.36E-16**	**5.81E-12**	**5.85E-12**	**2.44E-09**
Total	**4320000**	**1.91E-13**	**2.58E-15**	**2.53E-11**	**2.55E-11**	**1.06E-08**
				Total including ingestion:	**2.71E-11**	**1.13E-08**

High-Ci releases are due to very short-lived isotopes.
Almost 100% of activity decays occurs before material reaches the ground
Total individual dose integrated over 50 yrs is 10^{-8} of annual natural background for 1 yr

Summary

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- Developed a model for radionuclide transport to earth from a NTR firing in low earth orbit
- Included relevant radionuclides and daughter nuclides
- Initial released nuclide inventory scaled to measured Phoebus-1B test releases
- Total dose per person was 27 picoSieverts
- This is 100,000,000 times lower than the annual dose per person from natural background radiation